Cosmological Signatures of Dark Photons

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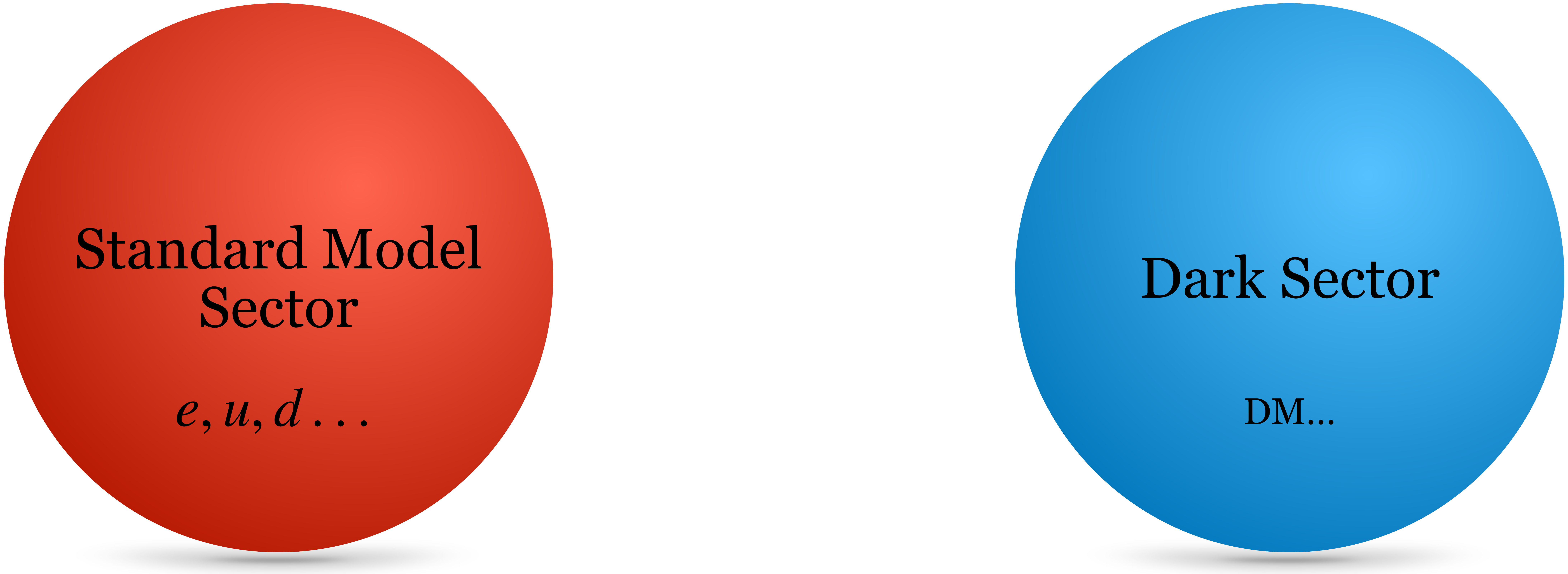
NYU & Princeton

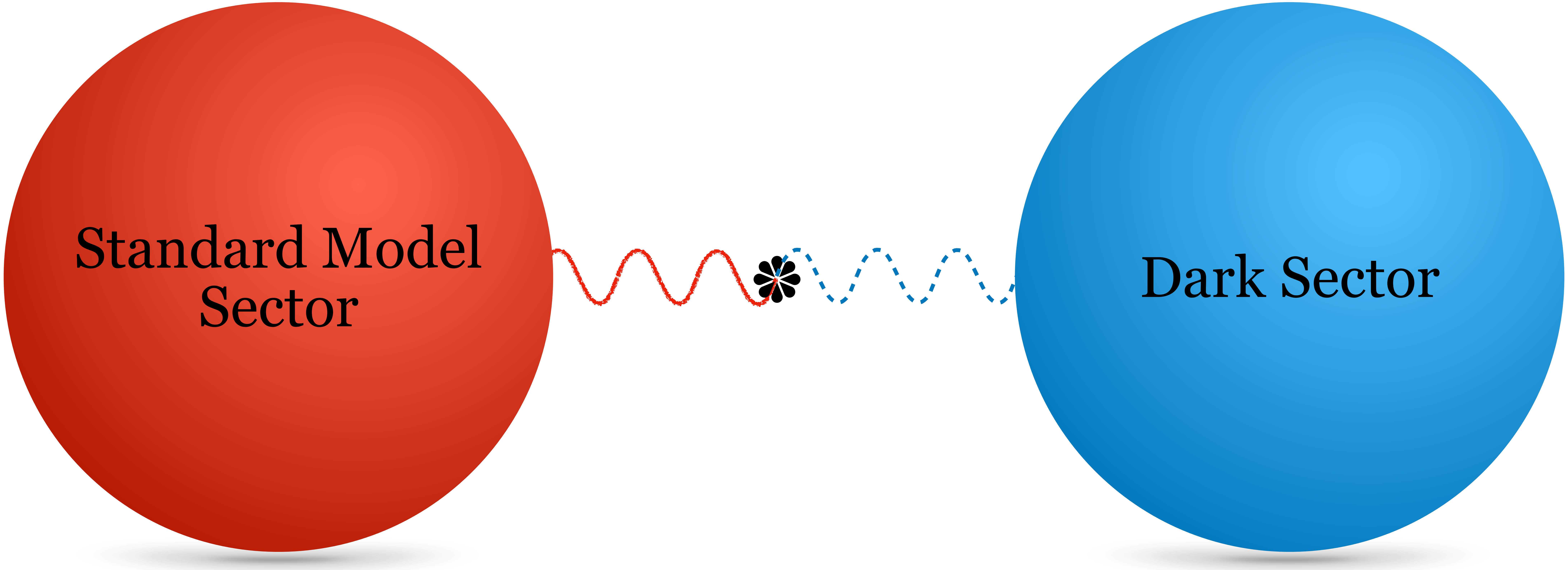
based on 2002.05165, 2004.06733, 2206.13520
with James Bolton, Andrea Caputo, Siddharth Mishra-Sharma, Joshua Ruderman, and Matteo Viel

Dark Sectors



Sectors are mostly separate with their own interactions...

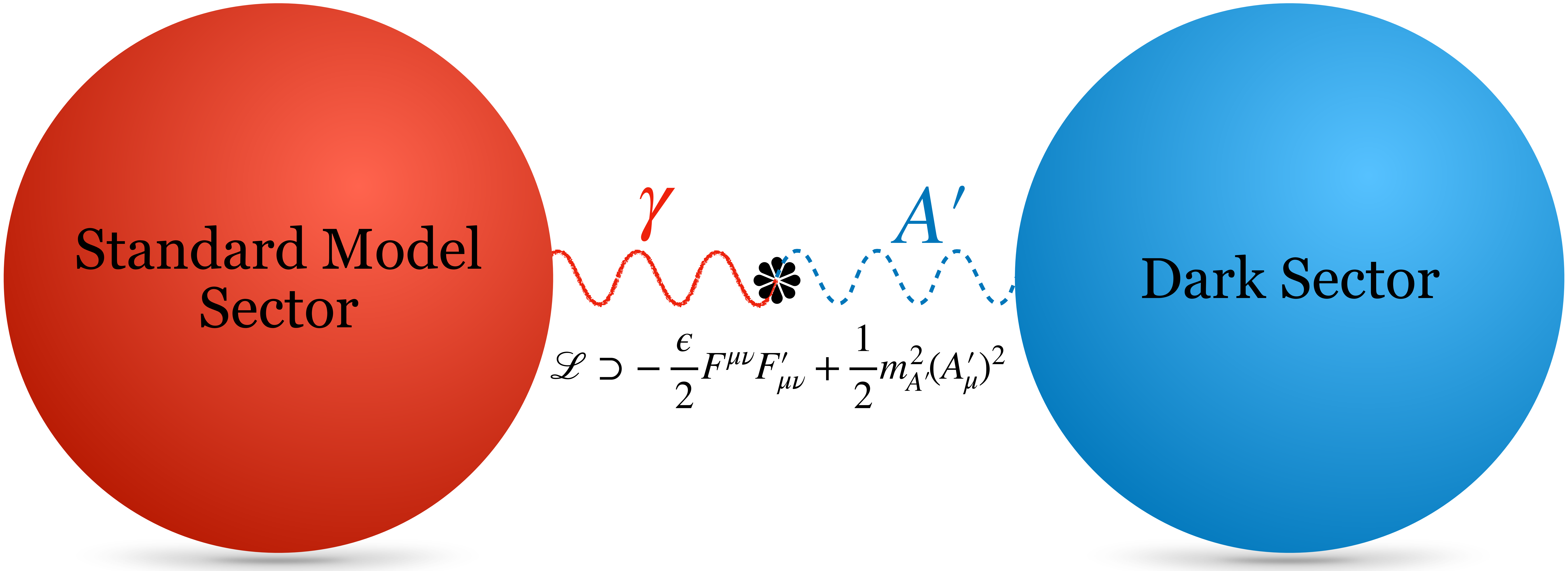
Dark Sector



... with a **mediator** possessing some **small mixing** with the SM.

Holdom Phys. Lett. 166B, 196 (1986)

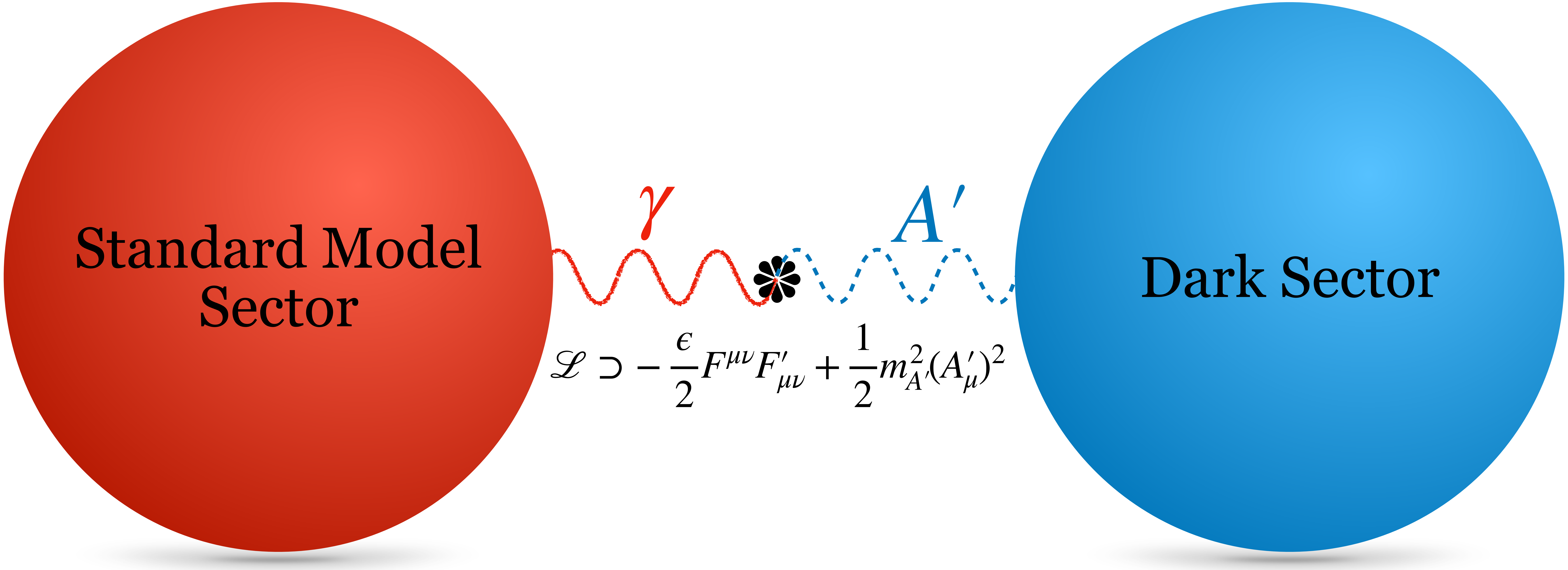
Dark Photons



Vector mediator of the dark sector.

Mixing with SM photon generated by UV physics.

Dark Photons

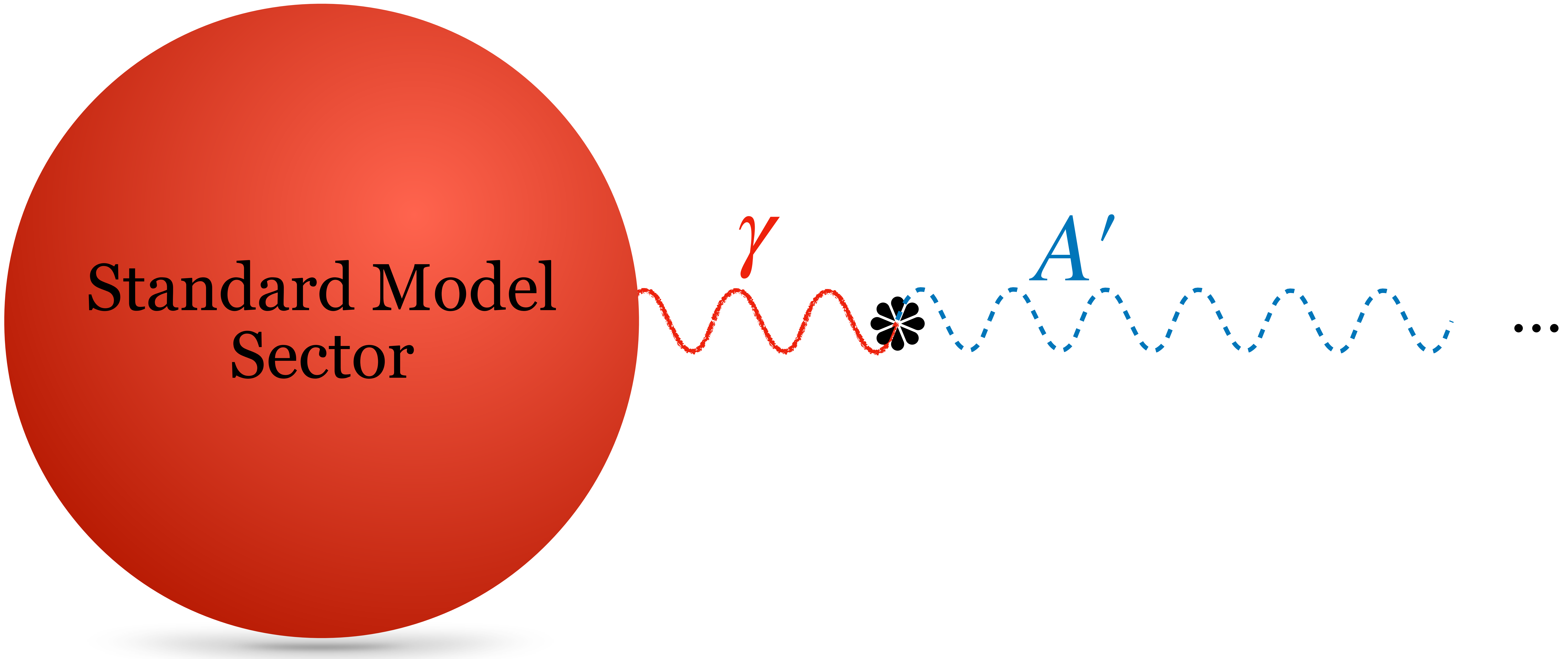


$$\mathscr{L} \supset -\frac{\epsilon}{2} F^{\mu\nu} F'_{\mu\nu} + \frac{1}{2} m_{A'}^2 (A'_\mu)^2$$

Simple, **renormalizable** interaction between two sectors.

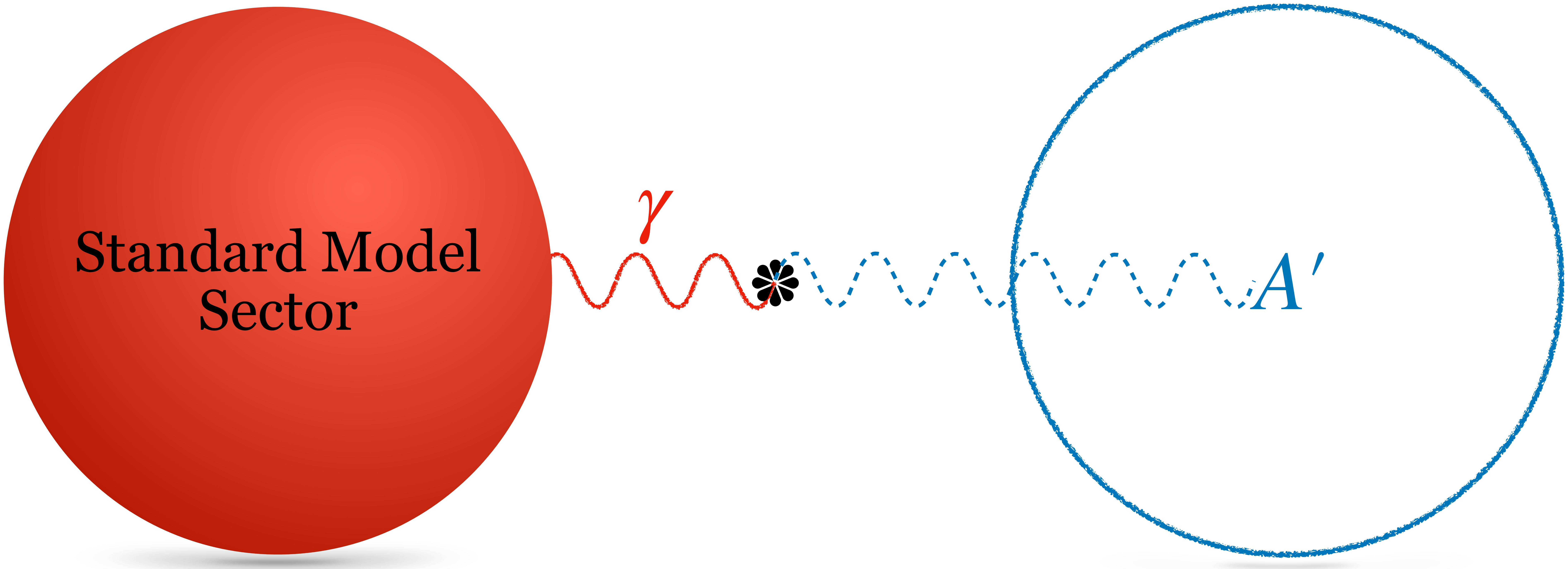
Two parameters: **mixing** ϵ and **mass** $m_{A'}$.

Scenario I: Dark Photon Existence



The existence of the dark photon, **with no further assumptions**, already leads to cosmological signatures.

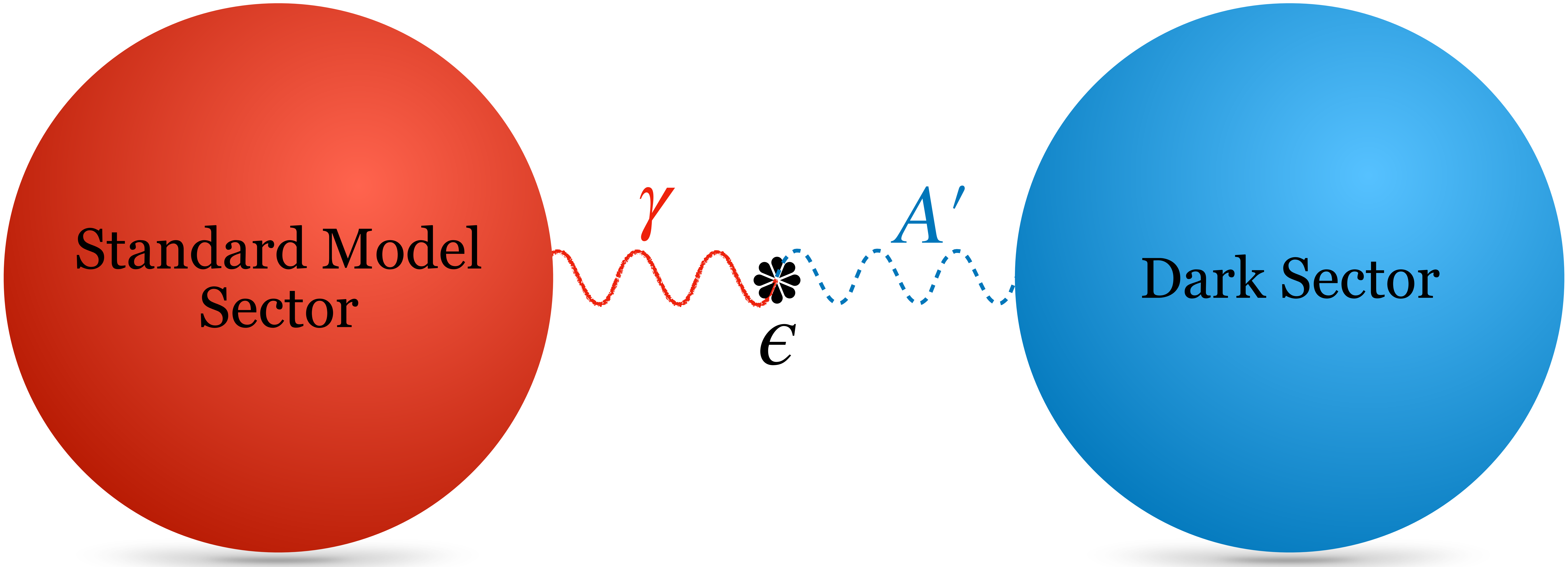
Scenario II: Dark Photon Dark Matter



Light dark photons may even be **all of dark matter** itself: additional and distinct cosmological signatures.

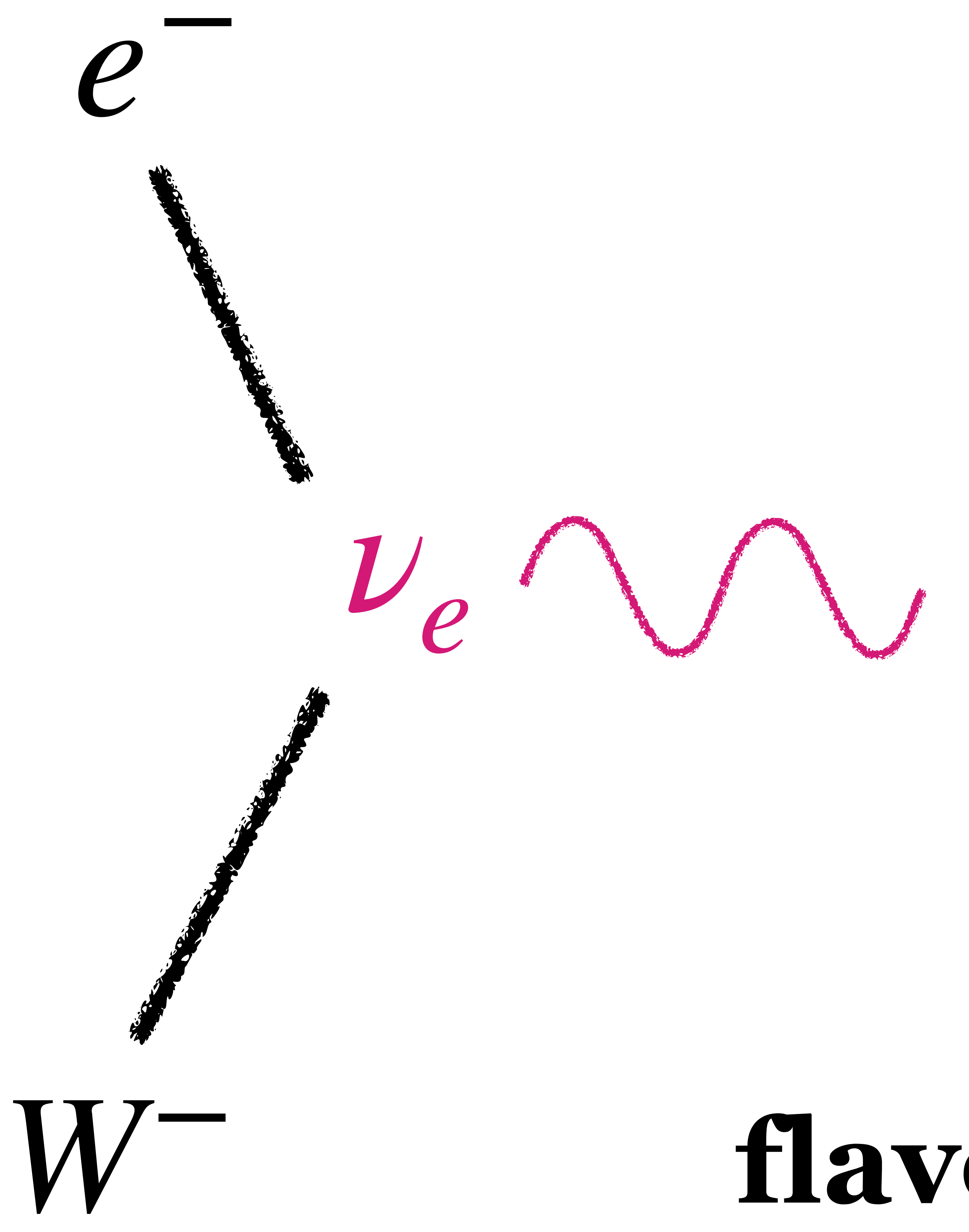
Why Cosmology?

Dark Photon Oscillations



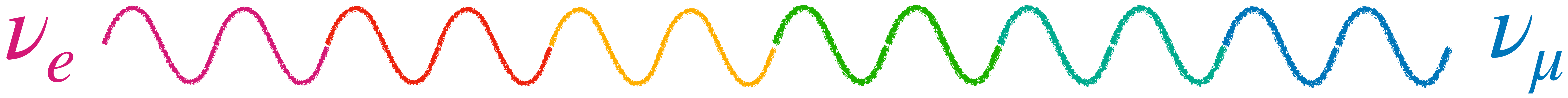
SM charged under **interaction eigenstate** of the photon, which is **not a propagation eigenstate**.

Mixing in Neutrinos



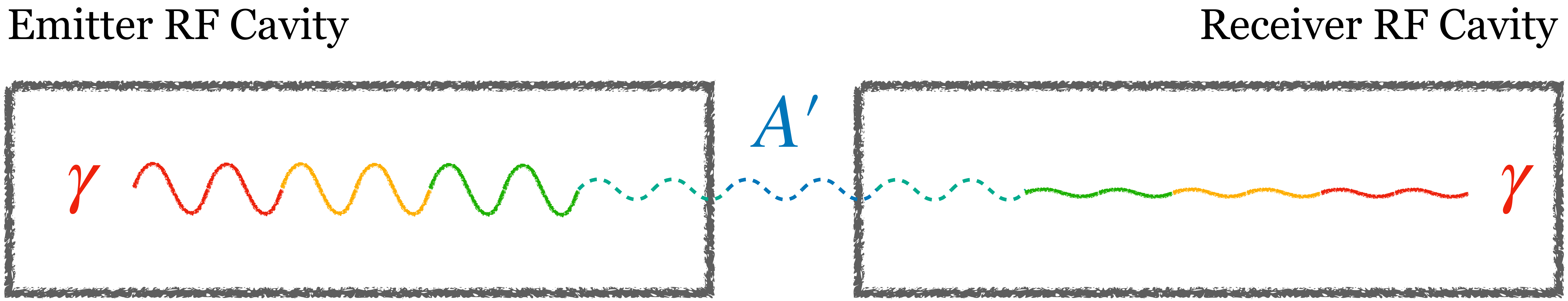
Neutrinos are produced in
flavor or **interaction eigenstates**…

Neutrino Oscillations



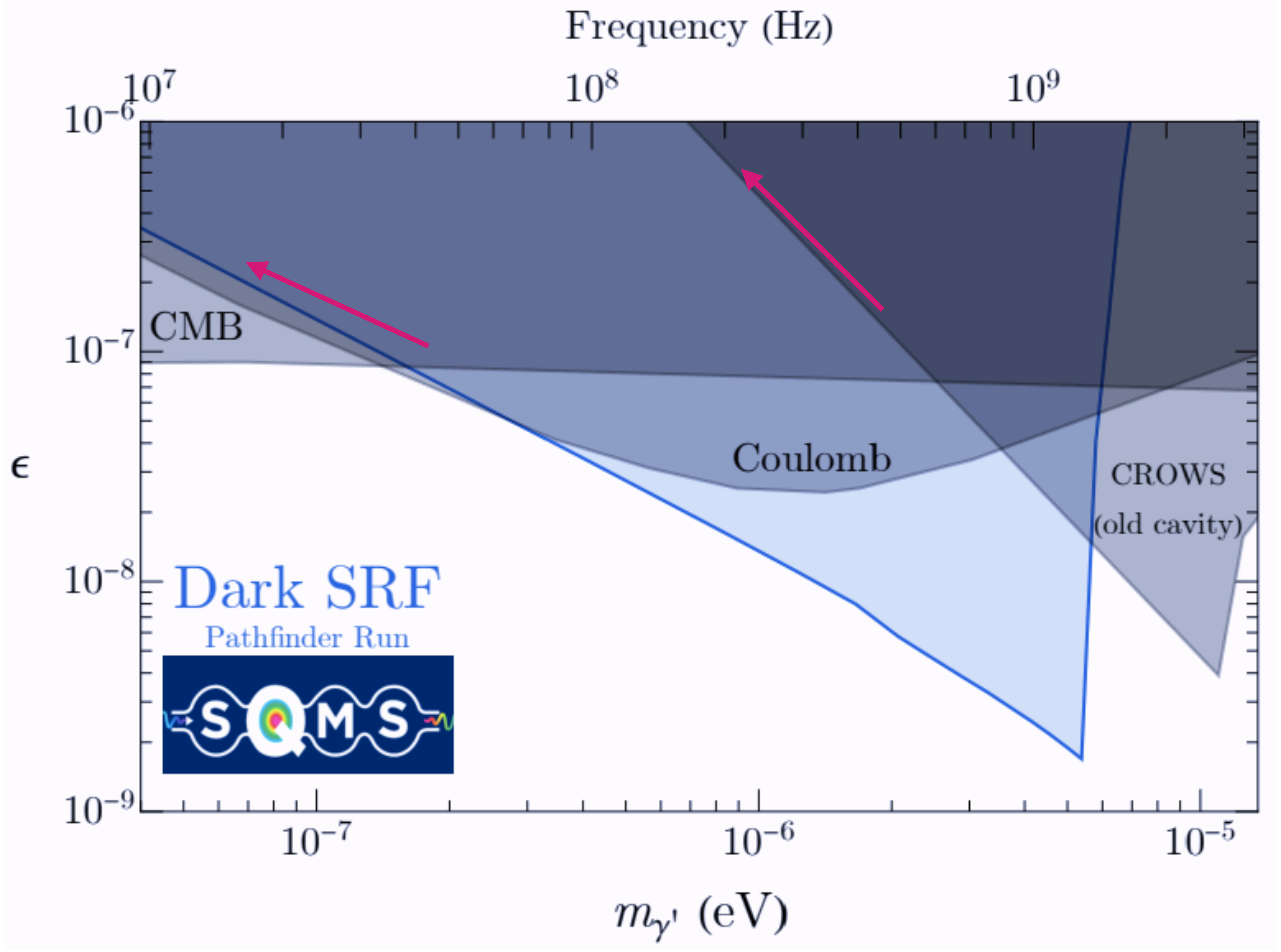
… that are not **propagation eigenstates**.

Light-Shining-Through-Wall

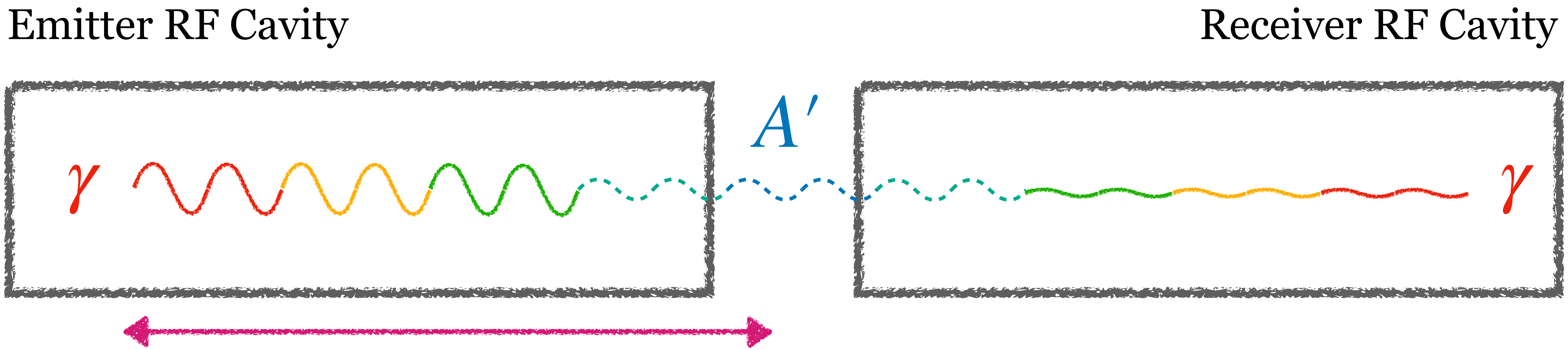


Photons can likewise oscillate into dark photons **in vacuum**.

DarkSRF


Frequency (Hz)
10^7
10^8
10^9
10^{-6}
10^{-7}
10^{-8}
10^{-9}
ϵ
CMB
Coulomb
CROWS (old cavity)
Dark SRF
Pathfinder Run
SQMS
10^{-7}
10^{-6}
10^{-5}
$m_{\gamma'}$ (eV)

Light-Shining-Through-Wall

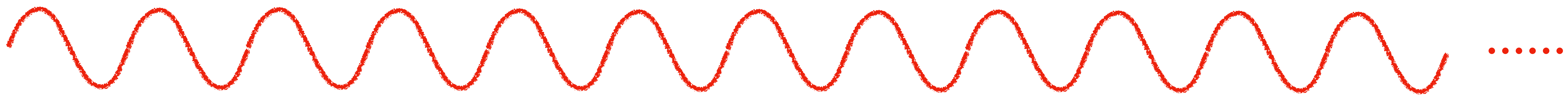


$$L \sim \frac{\omega}{m_{A'}^2} \sim 0.8\,\mathrm{m} \left(\frac{10^{-6}\,\mathrm{eV}}{m_{A'}} \right)^2 \left(\frac{\nu}{\mathrm{GHz}} \right)$$

$$P_{\gamma \to A'} = 4\epsilon^2 \sin^2 \left(\frac{m_{A'}^2 L}{4\omega} \right)$$

There is a characteristic **oscillation length** of **maximum** conversion.

Lighter Dark Photons

γ 

$$L \sim 10^6\,\mathrm{m}\left(\frac{10^{-9}\,\mathrm{eV}}{m_{A'}}\right)^2\left(\frac{\nu}{\mathrm{GHz}}\right)$$

$$P_{\gamma\to A'} = 4\epsilon^2\sin^2\left(\frac{m_{A'}^2 L}{4\omega}\right)$$

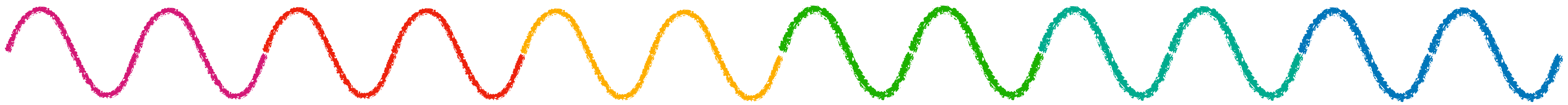
Reason #1 for Cosmology: Difficult with **terrestrial probes**.

Lighter Dark Photons

Reason #2 for Cosmology: **Propagation medium effects** can help.

Dark Photon Oscillations

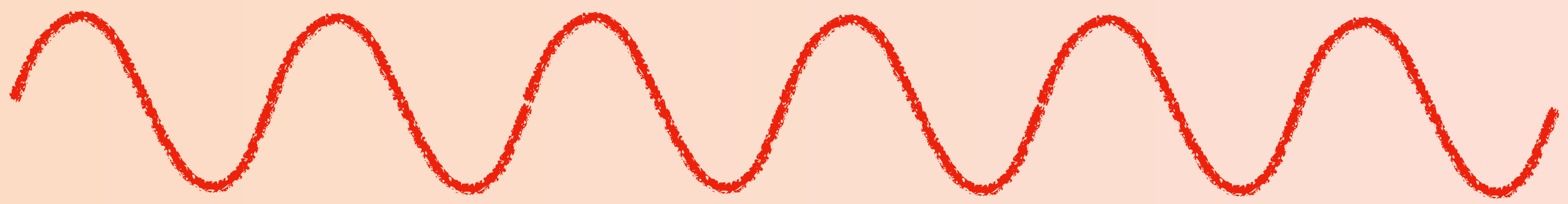
Nonresonant Oscillations



Photons are massless in vacuum. **Energy gap** between γ and A' lead to **nonresonant oscillations** (like neutrinos).

Photon Plasma Mass

γ



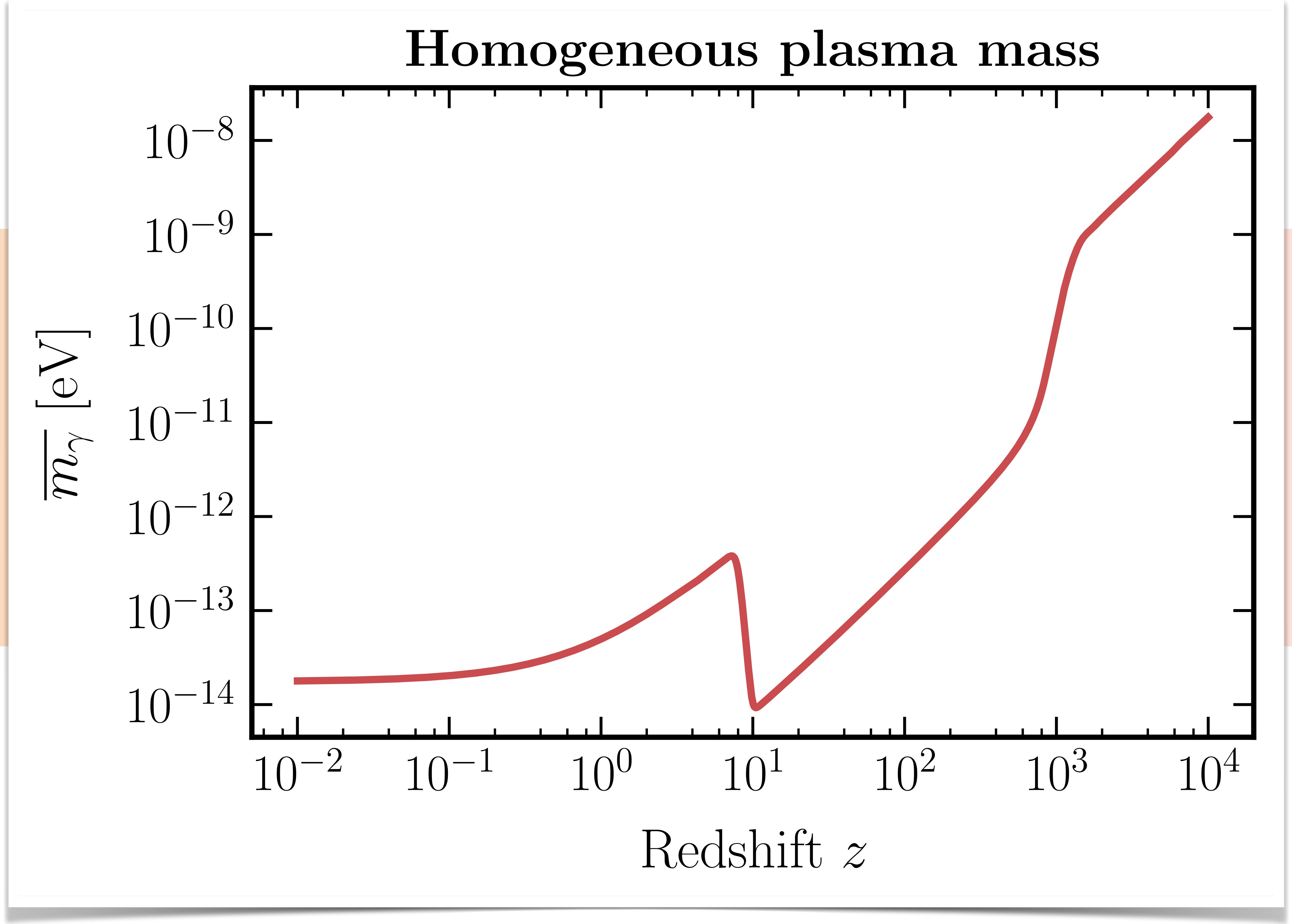
m_γ

$$m_\gamma \simeq 2 \times 10^{-14}\,\mathrm{eV} \left(\frac{n_\mathrm{e}}{2.5 \times 10^{-7}\,\mathrm{cm}^{-3}} \right)^{1/2}$$

mean electron number density today

But photons pick up an **effective mass** in a **plasma**.

Homogeneous Plasma Mass



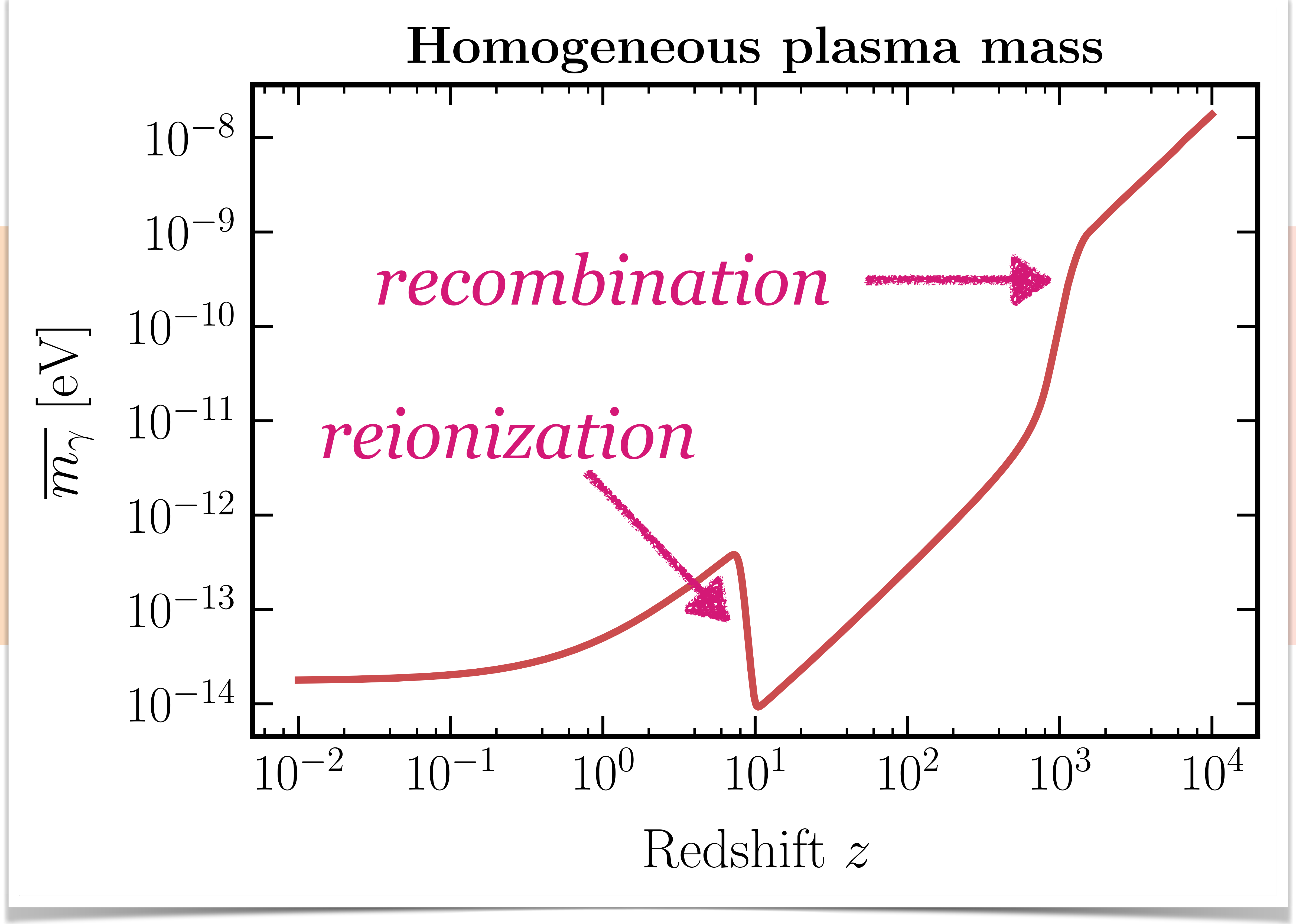
free electron fraction

$$\overline{m_\gamma} \simeq 2 \times 10^{-14}\,\text{eV}\,(\overline{n_{\text{e},0}}x_\text{e})^{1/2}(1+z)^{3/2}$$

mean electron number density today

Under the assumption of **homogeneity**,
$10^{-14}\,\text{eV} \lesssim \overline{m_\gamma} \lesssim 10^{-9}\,\text{eV}$ after recombination.

Homogeneous Plasma Mass



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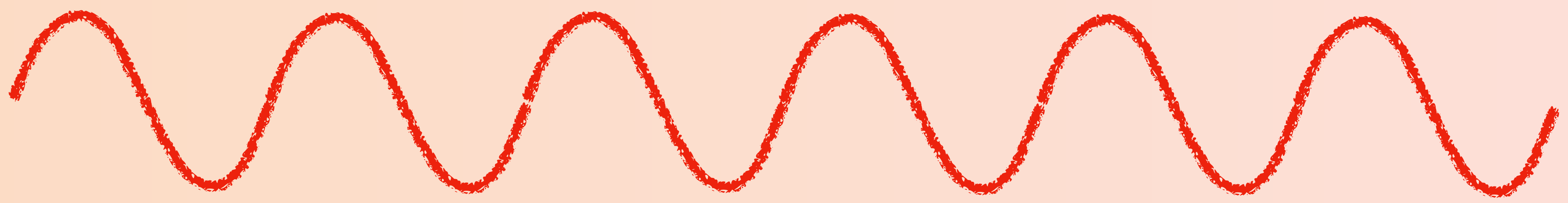
Resonant Oscillations

$$\hat{\mathrm{H}} = \frac{1}{4\omega}\begin{pmatrix} m_\gamma^2 - m_{A'}^2 & 2\epsilon m_{A'}^2 \\ 2\epsilon m_{A'}^2 & -m_\gamma^2 + m_{A'}^2 \end{pmatrix}$$

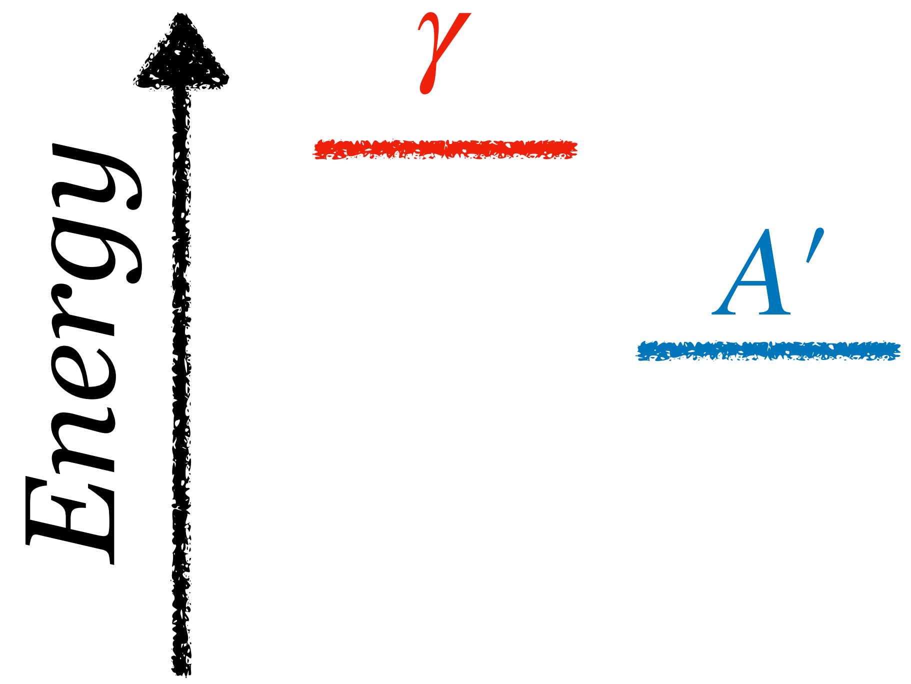
$\longrightarrow$ *later time, decreasing redshift*

γ



$m_\gamma \gg m_{A'}$

$\longrightarrow$ *decreasing* $\overline{n_{\mathrm{e}}}$ *and* $\overline{m_\gamma}$



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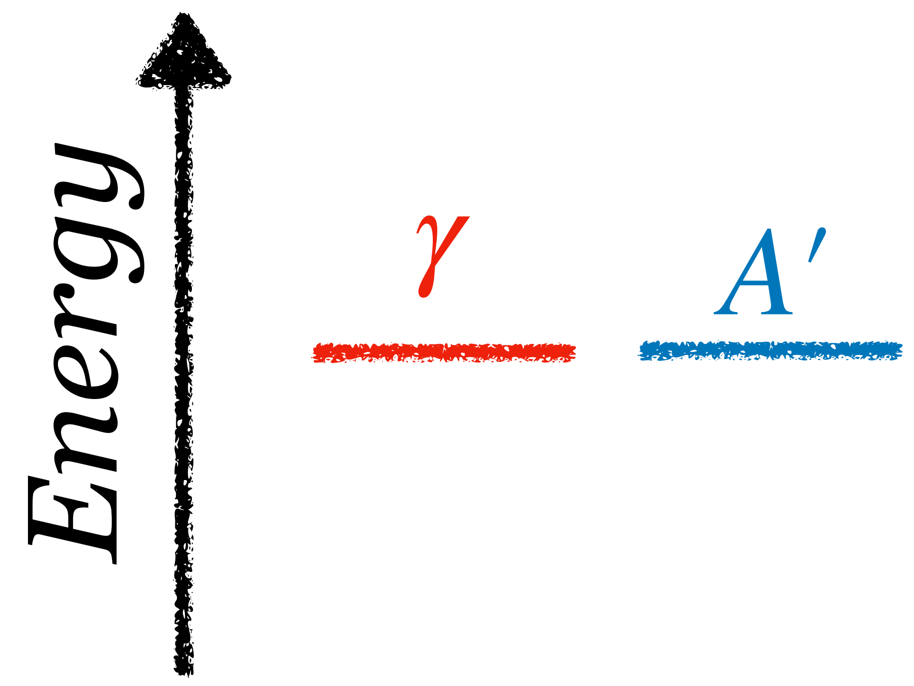
later time, decreasing redshift

decreasing $\overline{n_e}$ and $\overline{m_\gamma}$



Resonant Oscillations

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later time, decreasing redshift

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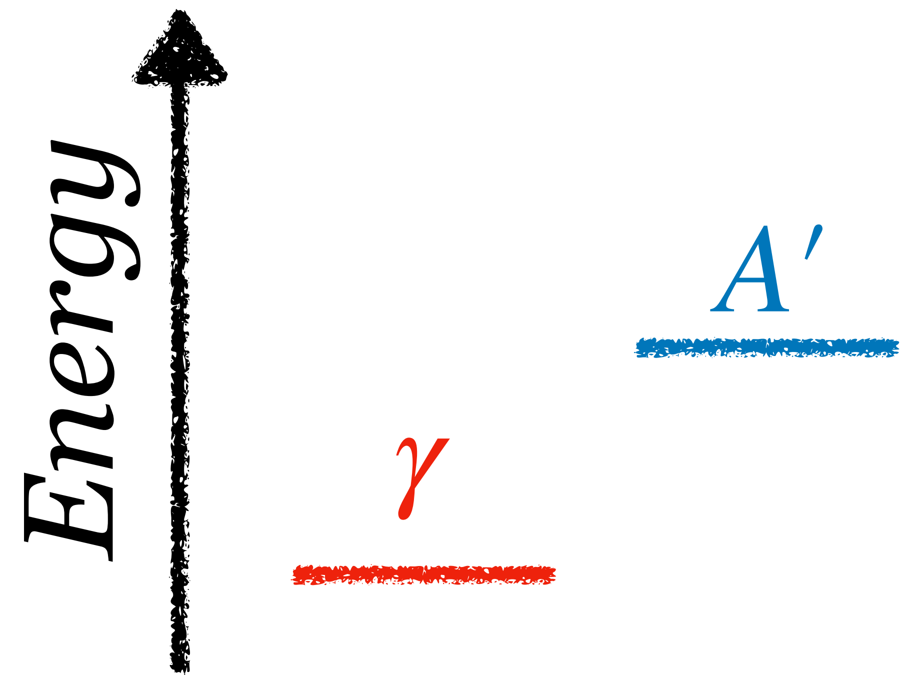


Resonant Oscillations

→ *later time, decreasing redshift*

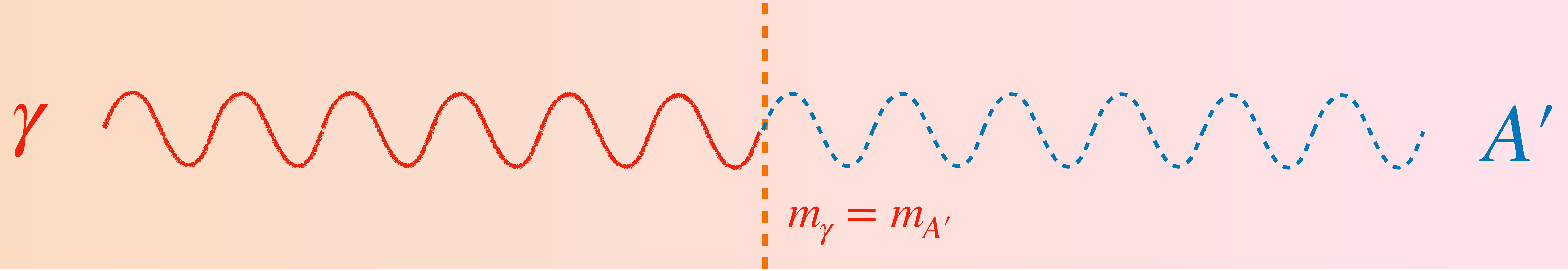
→ *decreasing* $\overline{n_\mathrm{e}}$ *and* $\overline{m_\gamma}$

$$P_{\gamma \to A'} = \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{\mathrm{d} \ln m_\gamma^2}{\mathrm{d}t} \right|^{-1}_{m_\gamma = m_{A'}}$$

Resonant Oscillations

$$P^{\text{vac}}_{\gamma\to A'} \sim 4\epsilon^2 \sin\left(\frac{m_{A'}^2 L}{4\omega}\right) \sim 2 \times \epsilon^2 \times \frac{m_{A'}^2}{2\omega} \times L$$

→ *later time, decreasing redshift*



→ *decreasing $\overline{n_e}$ and $\overline{m_\gamma}$*

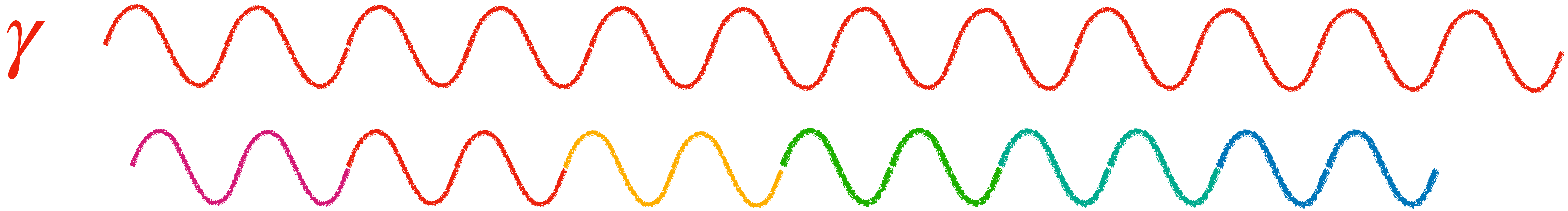
mixing

$(\gamma \to A'$ *vacuum oscillation length*$)^{-1}$

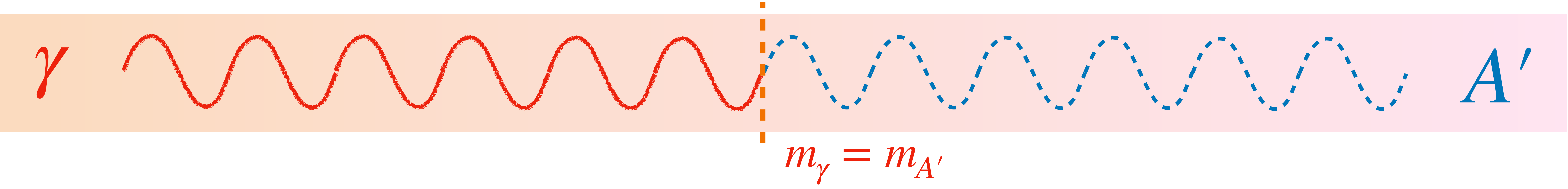
resonance timescale $\sim H^{-1}$

$$P_{\gamma\to A'} = 2\pi \times \epsilon^2 \times \frac{m_{A'}^2}{2\omega} \times \left|\frac{\mathrm{d}\ln m_\gamma^2}{\mathrm{d}t}\right|^{-1}_{m_\gamma = m_{A'}}$$

Takeaways



1. Cosmological scales good for long oscillation length.



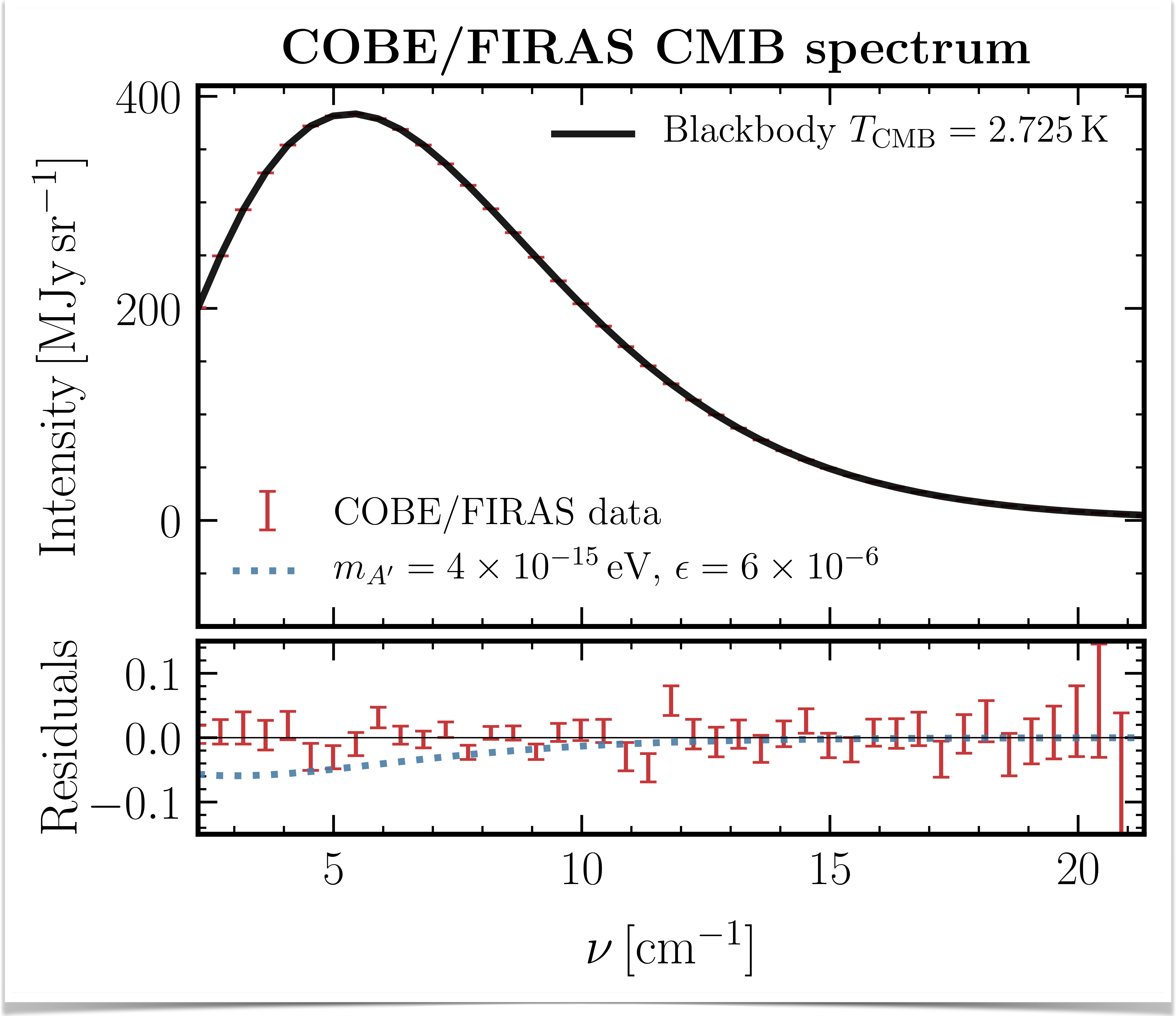
2. Resonant oscillations due to medium effects are important cosmologically.

Resonant Oscillations in the Real Universe

see also:

Bondarenko+ 2002.08942
A. A. Garcia+ 2003.10465
Witte+ 2003.13698

Cosmic Microwave Background

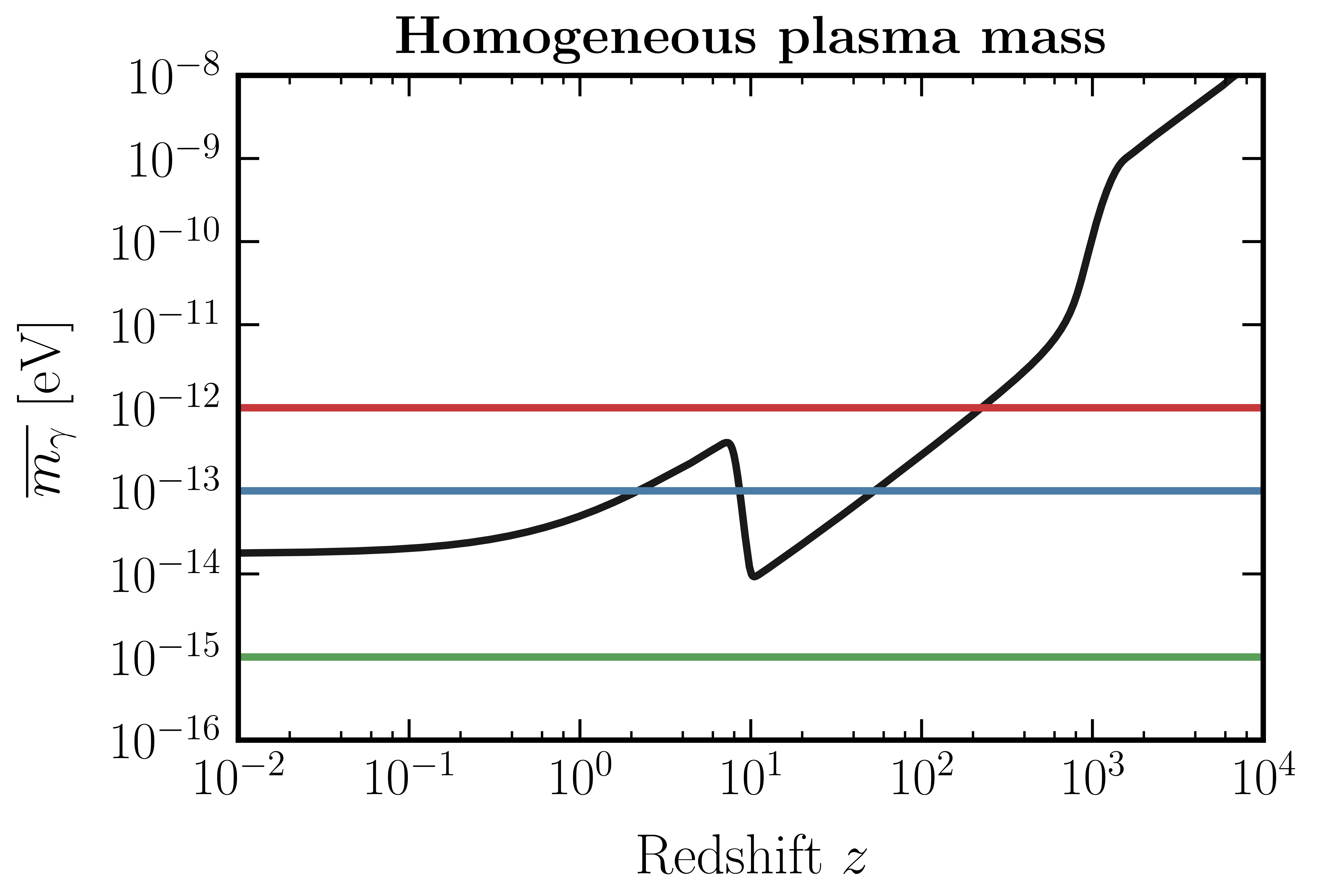


The CMB is very close to a **perfect blackbody**.

Spectral distortions due to $\gamma \to A'$ disappearance highly constrained.

$$P_{\gamma\to A'} = \sum_i \frac{\pi\epsilon^2 m_{A'}^2}{\omega} \left| \frac{\mathrm{d}\ln m_\gamma^2}{\mathrm{d}t} \right|^{-1}_{t_i = t_{\rm res}}$$

Resonant Oscillations



$$P_{\gamma\to A'} = \sum_i \frac{\pi\epsilon^2 m_{A'}^2}{\omega} \left|\frac{\mathrm{d}\ln m_\gamma^2}{\mathrm{d}t}\right|^{-1}_{t_i=t_{\mathrm{res}}}$$

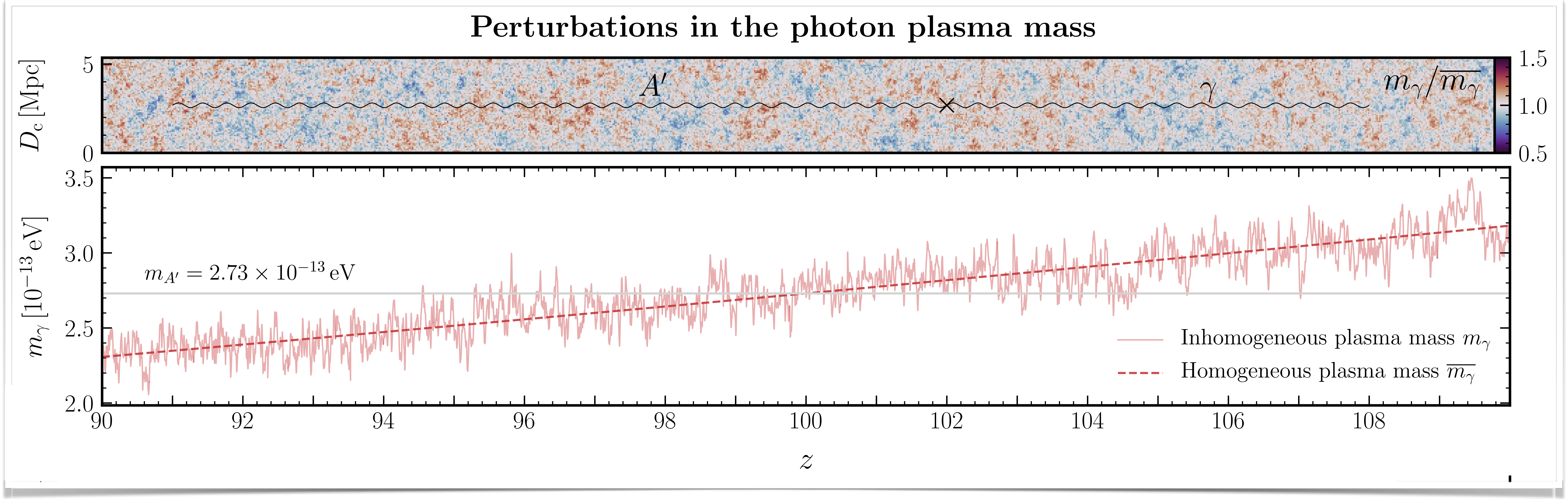
Resonant oscillations when

$$m_\gamma = m_{A'} .$$

Conversions after recombination covers

$$10^{-14}\,\mathrm{eV} \lesssim m_{A'} \lesssim 10^{-9}\,\mathrm{eV} .$$

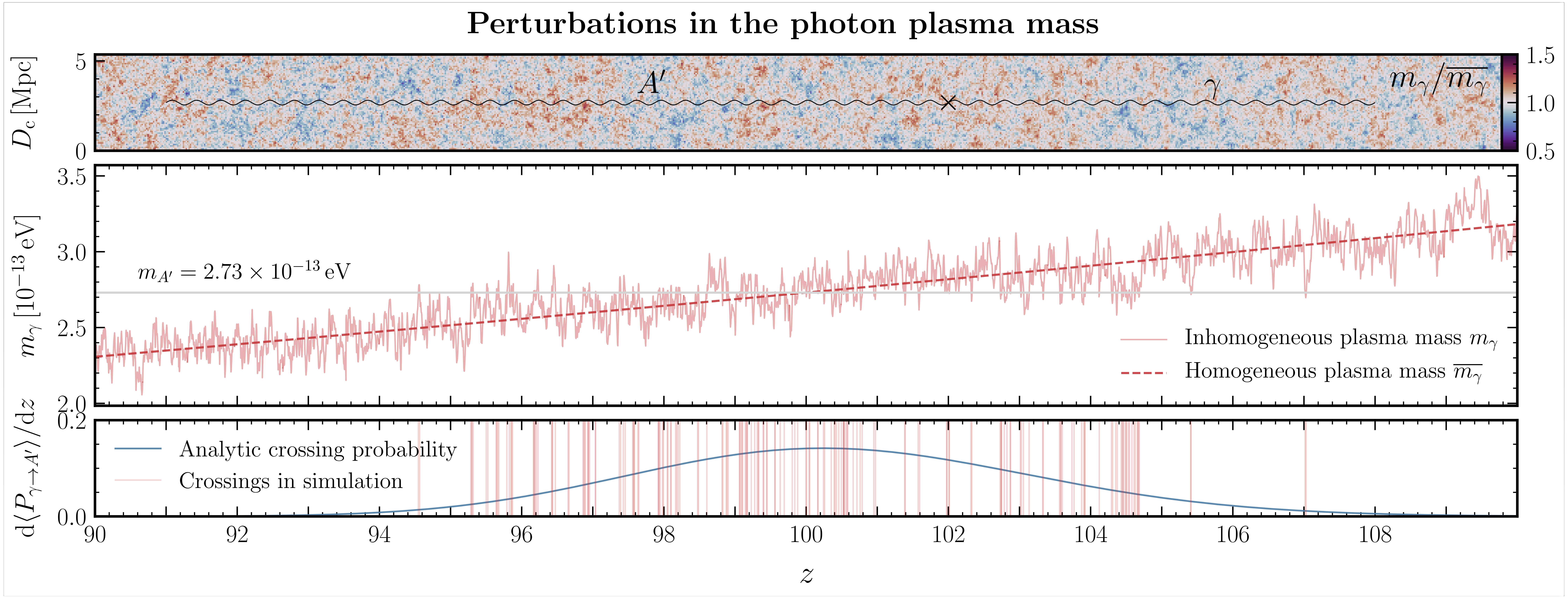
Inhomogeneities



Fluctuations in electron density means $m_\gamma \neq \overline{m_\gamma}$.

Numerous resonance crossings along each photon path...

Analytic Formalism



... but we can **average over photon paths** analytically!

Analytic Formalism

$$P_{\gamma \to A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|_{t_i = t_\mathrm{res}}^{-1} = \int \mathrm{d}t \, \frac{\pi \epsilon^2 m_{A'}^2}{\omega(t)} \, \delta_\mathrm{D}(m_\gamma^2 - m_{A'}^2) \, m_\gamma^2$$

Change of integration measure

Analytic Formalism

$$P_{\gamma\to A'} = \int \mathrm{d}t \, \frac{\pi\epsilon^2 m_{A'}^2}{\omega(t)} \, \delta_{\mathrm{D}}(m_\gamma^2 - m_{A'}^2) \, m_\gamma^2$$

Average over distribution of m_γ^2

(time-dependent) probability density function of m_γ^2

$$\langle P_{\gamma\to A'} \rangle = \int \mathrm{d}t \int \mathrm{d}m_\gamma^2 \, f(m_\gamma^2; t) \, \frac{\pi\epsilon^2 m_{A'}^2}{\omega(t)} \, \delta_{\mathrm{D}}(m_\gamma^2 - m_{A'}^2) \, m_\gamma^2$$

Analytic Formalism

$$\langle P_{\gamma\to A'}\rangle = \int \mathrm{d}t \int \mathrm{d}m_\gamma^2\, f(m_\gamma^2;t)\,\frac{\pi\epsilon^2 m_{A'}^2}{\omega(t)}\,\delta_{\mathrm{D}}(m_\gamma^2 - m_{A'}^2)\,m_\gamma^2$$

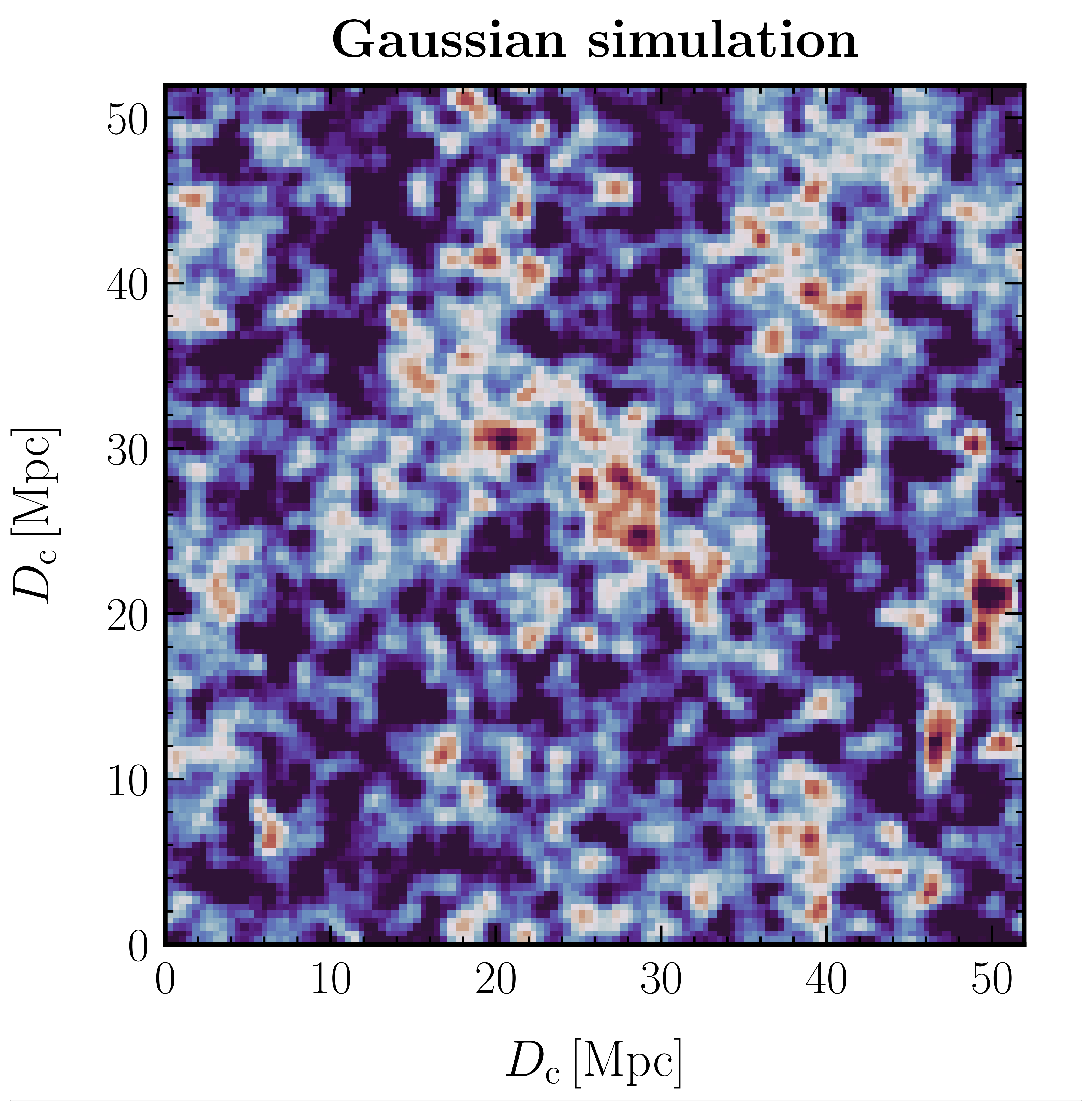
Integrate over m_γ^2

$$\langle P_{\gamma\to A'}\rangle = \int \mathrm{d}t\, f(m_\gamma^2 = m_{A'}^2;t)\,\frac{\pi\epsilon^2 m_{A'}^4}{\omega(t)}$$

Finding the average conversion probability reduces to knowing the **PDF of the plasma mass squared**.

One-Point PDF

$$m_\gamma \simeq 2 \times 10^{-14}\,\mathrm{eV} \left(\frac{n_\mathrm{e}}{2.5 \times 10^{-7}\,\mathrm{cm}^{-3}} \right)^{1/2} \left(\frac{x_\mathrm{e}}{1.0} \right)^{1/2}$$



$$m_\gamma^2 \propto n_\mathrm{e} \implies f(m_\gamma^2; t) \propto \mathscr{P}(\delta_\mathrm{b}; t)$$

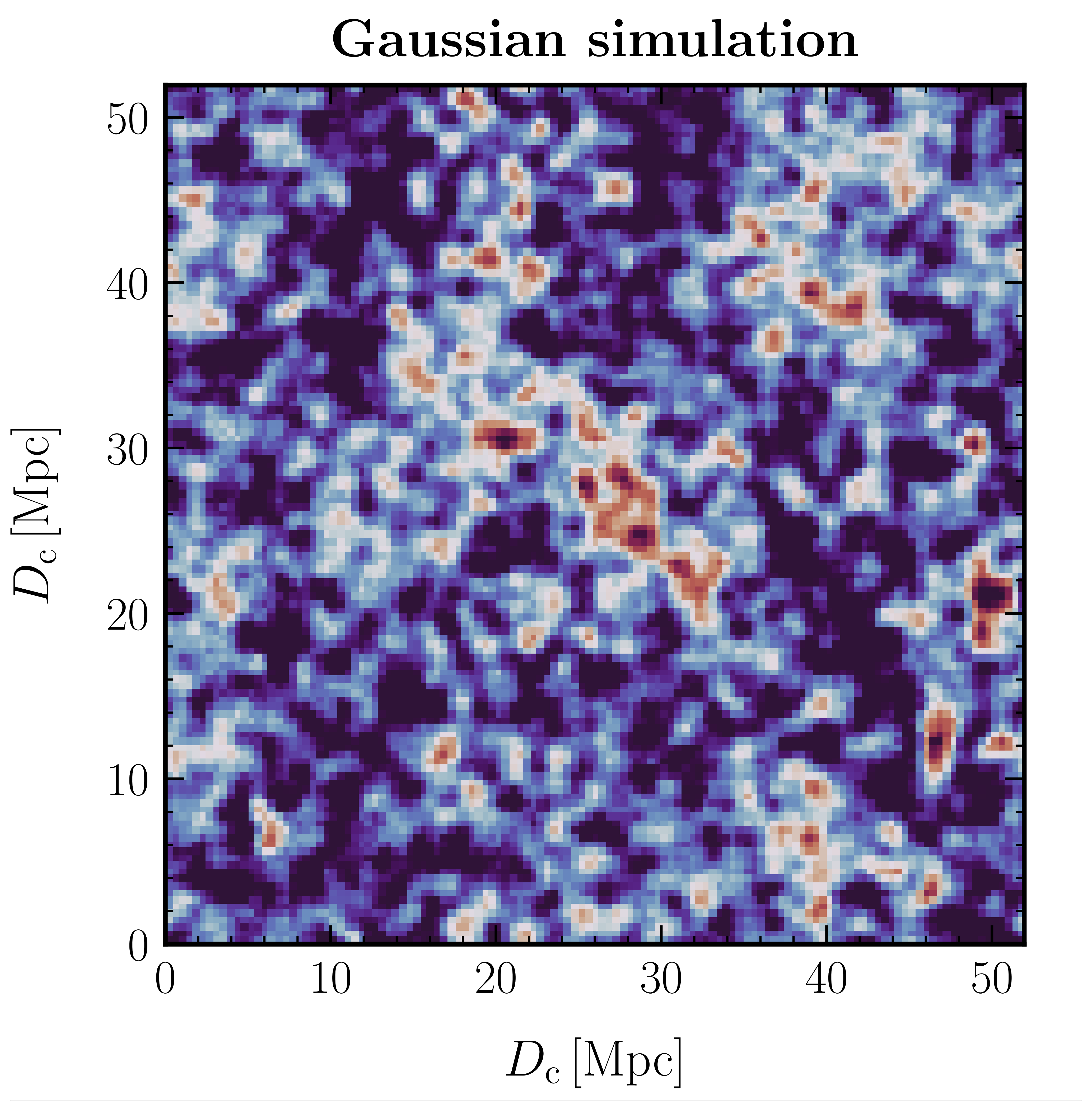
one-point PDF of baryon fluctuations

$$\delta_\mathrm{b} \equiv \frac{\rho_\mathrm{b} - \overline{\rho_\mathrm{b}}}{\overline{\rho_\mathrm{b}}}$$

m_γ^2 fluctuations directly related to **baryon density** fluctuations, a well-defined **cosmological parameter**.

Linear Regime

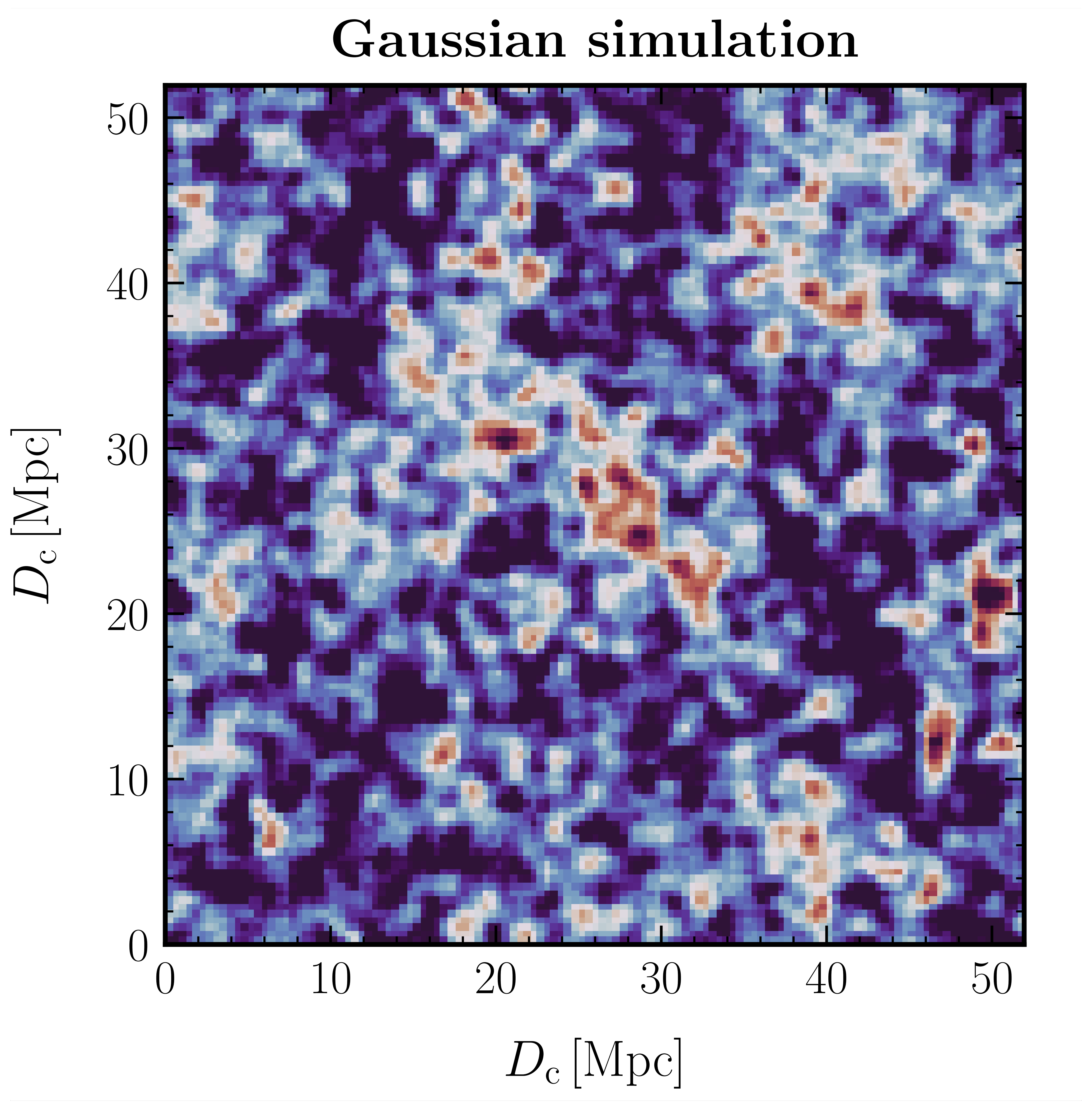
$$\delta_\mathrm{b} \equiv \frac{\rho_\mathrm{b} - \overline{\rho_\mathrm{b}}}{\overline{\rho_\mathrm{b}}}$$

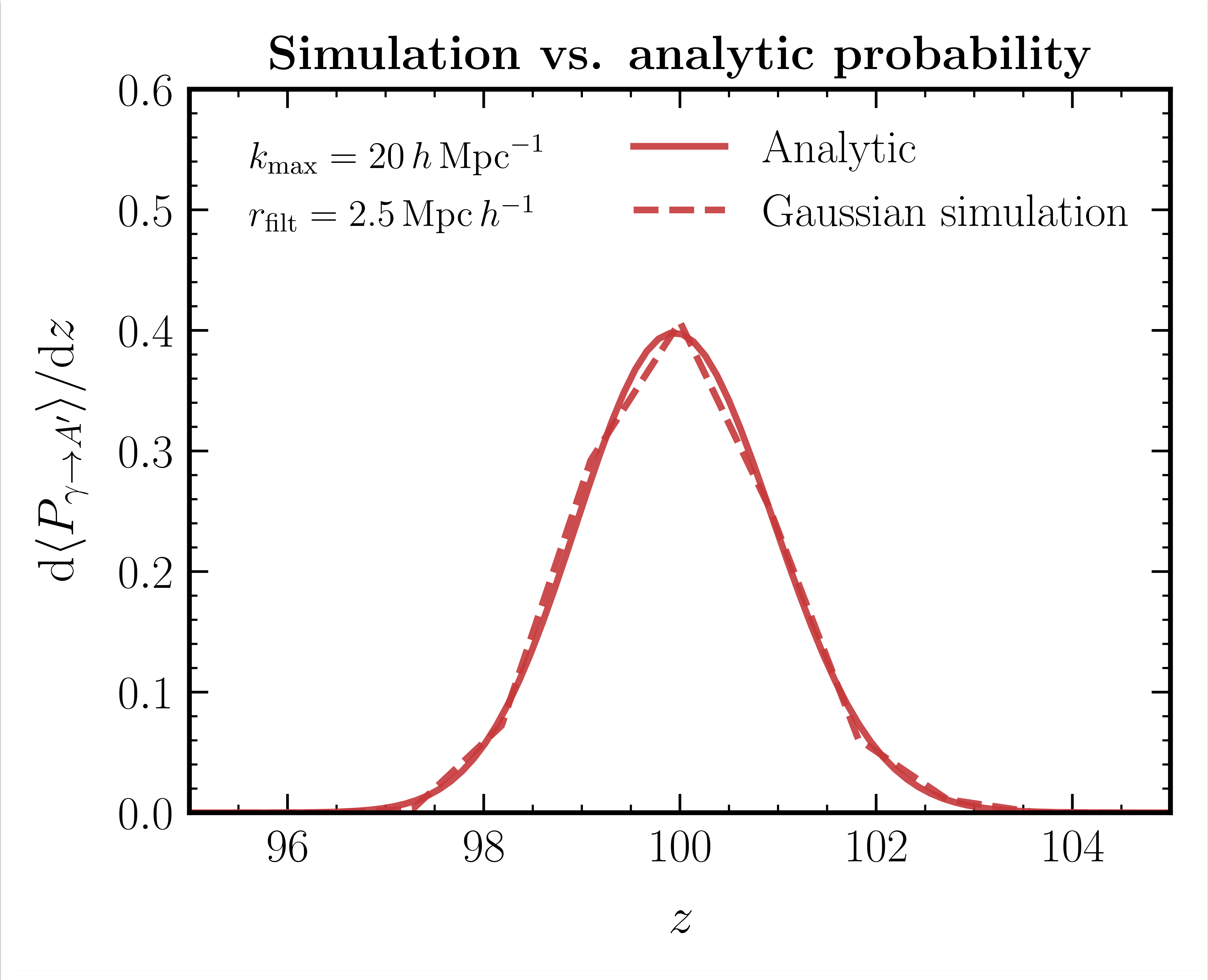


$$\mathscr{P}(\delta_\mathrm{b}; z) = \frac{1}{\sqrt{2\pi\sigma_\mathrm{b}^2(z)}} \exp\left(-\frac{\delta_\mathrm{b}^2}{2\sigma_\mathrm{b}^2(z)}\right)$$

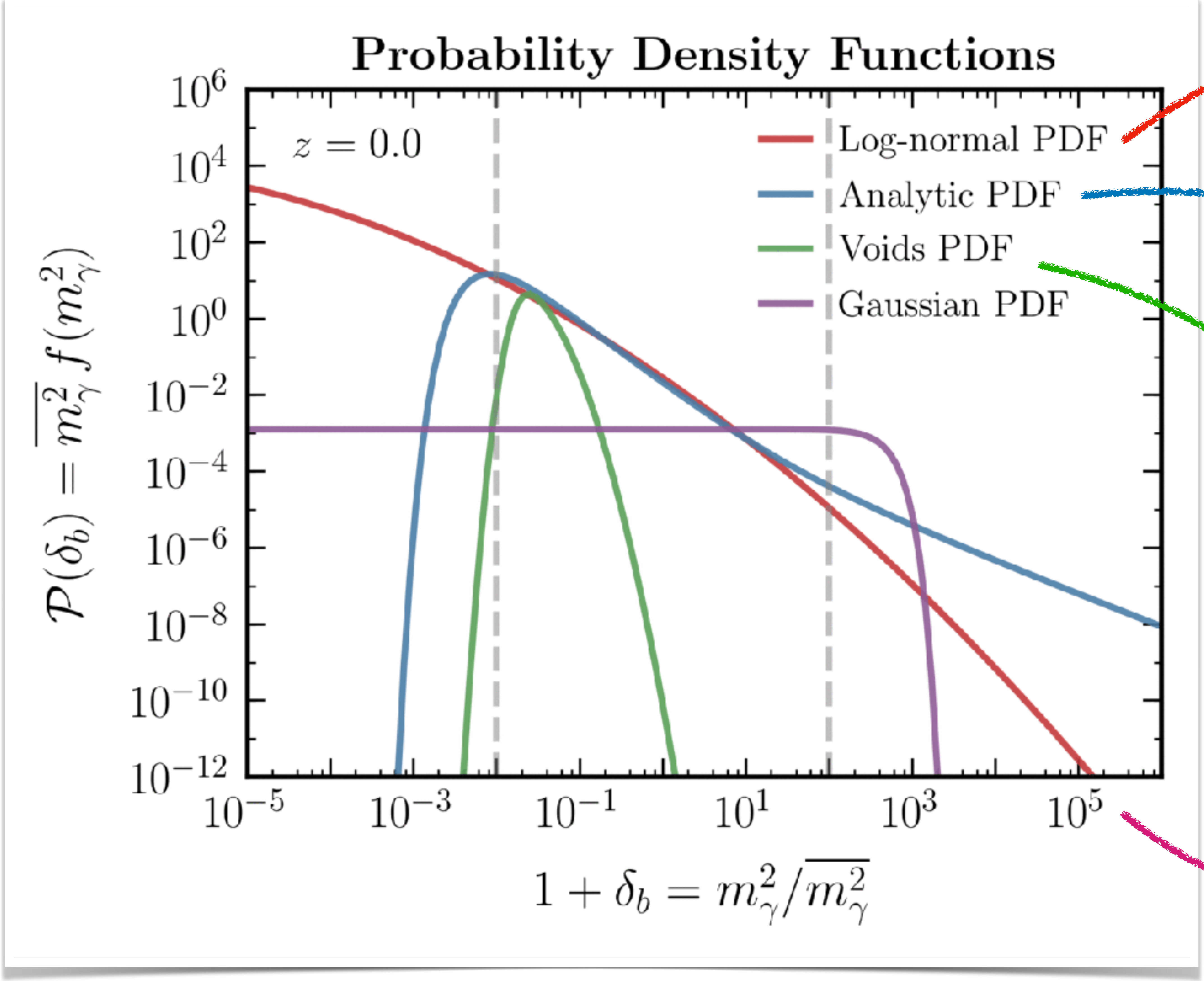
When $z \gg 20$, fluctuations are **small** and **Gaussian**, characterized fully by the **variance**, σ_b^2.

Analytic vs. Simulation





PDF in the Nonlinear Regime



phenomenological: variance from baryonic simulations.

theoretically motivated, but DM only.

Ivanov, Kaurov & Sibiryakov 1811.07913

fiducial

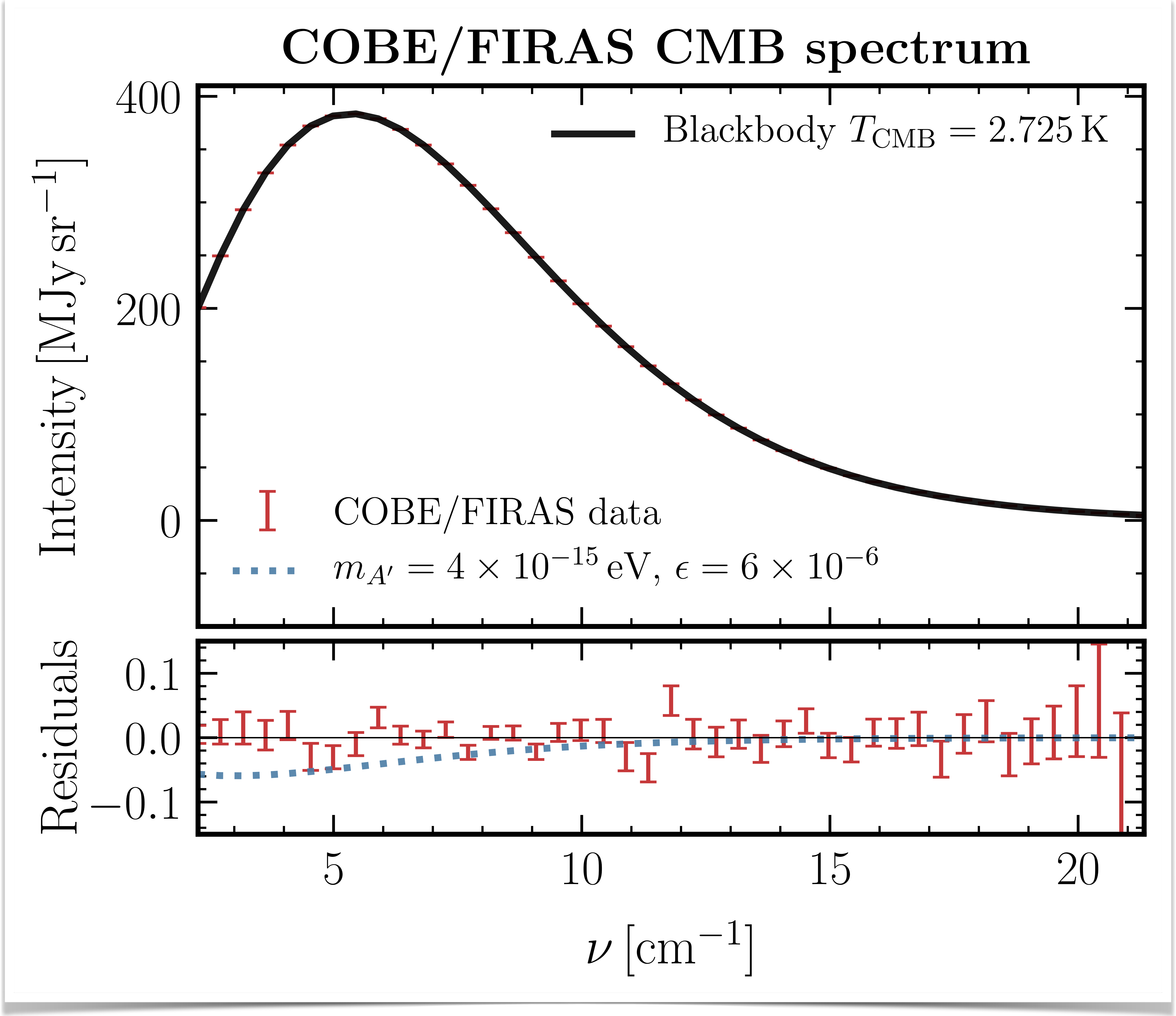
from simulations of voids: useful for underdensities

Adermann, Elahi, Lewis & Power 1703.04885, 1807.02938

good agreement between fiducial for $10^{-2} \leq 1 + \delta_b \leq 10^2$.

Constraints on Dark Photons Existing

Cosmic Microwave Background



The CMB is very close to a **perfect blackbody**.

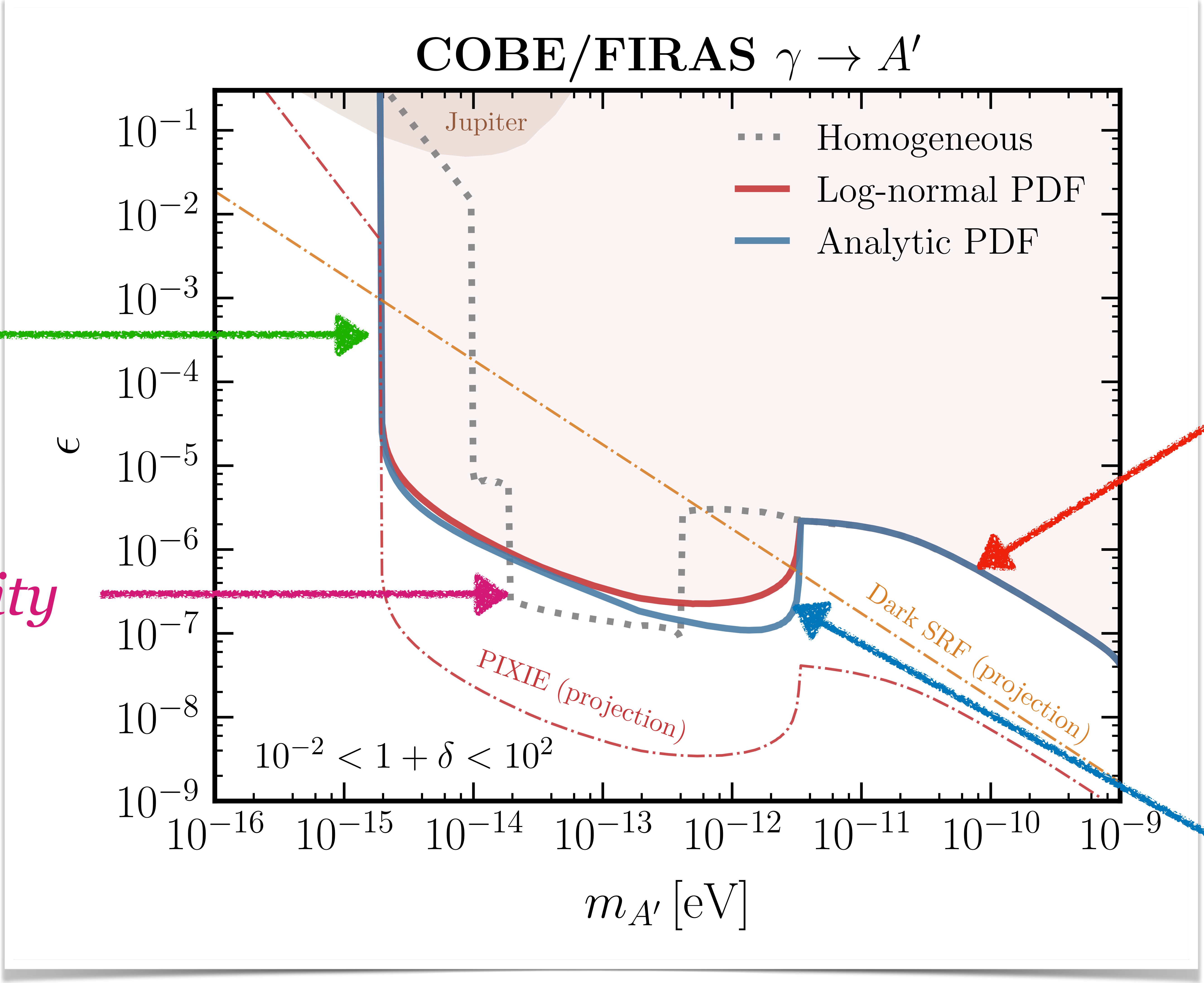
Spectral distortions due to disappearing photons are **highly constrained**.

$$P_{\gamma \to A'} = \sum_i \frac{\pi \epsilon^2 m_{A'}^2}{\omega} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1}_{t_i = t_{\rm res}}$$

Constraints with Inhomogeneities

conversions in underdensities at low redshifts

weakening as conversion probability pushed into future



inhomogeneities unimportant

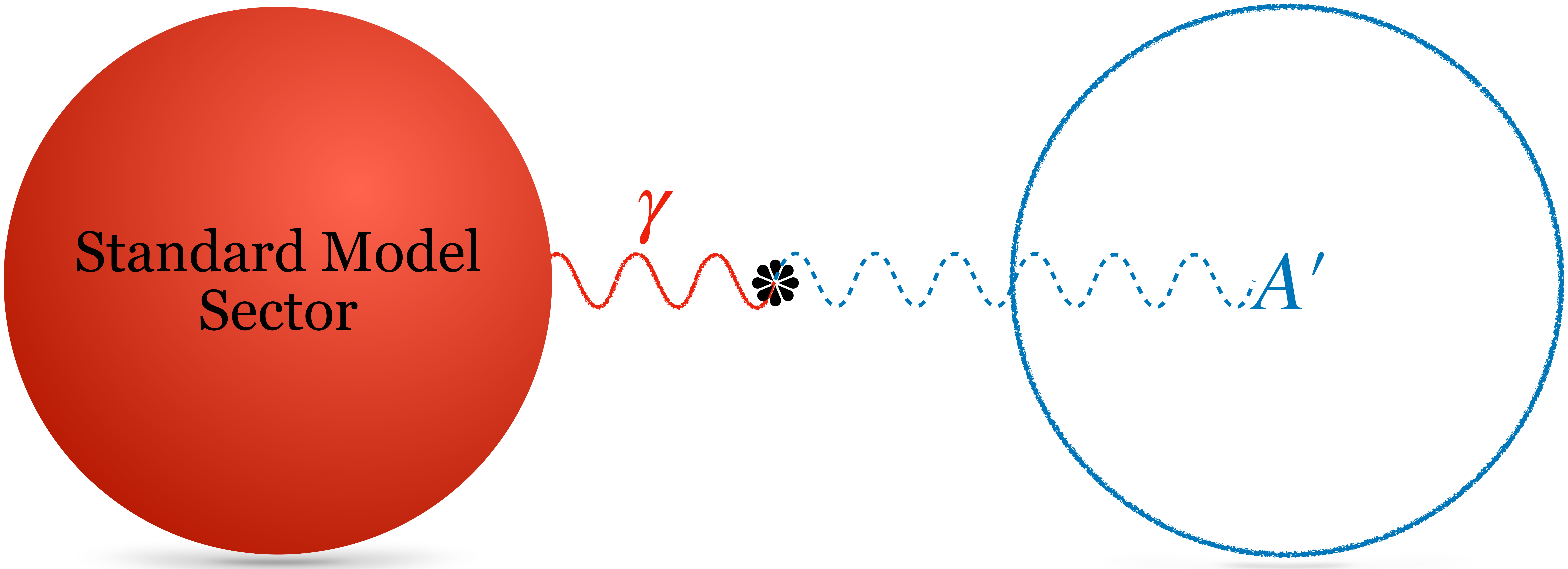
conversions in overdensities at reionization

Dark photons can be probed by cosmology.

Easy to include inhomogeneities!

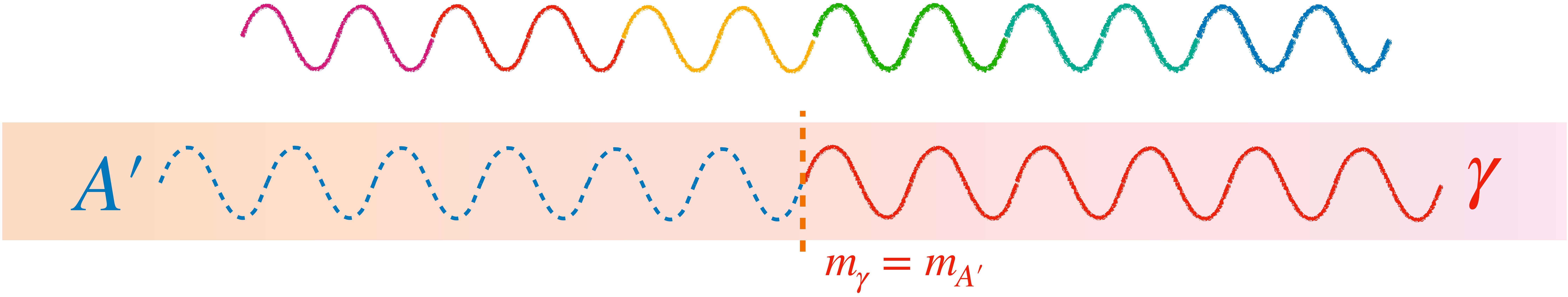
Dark Photon Dark Matter

Scenario II: Dark Photon Dark Matter

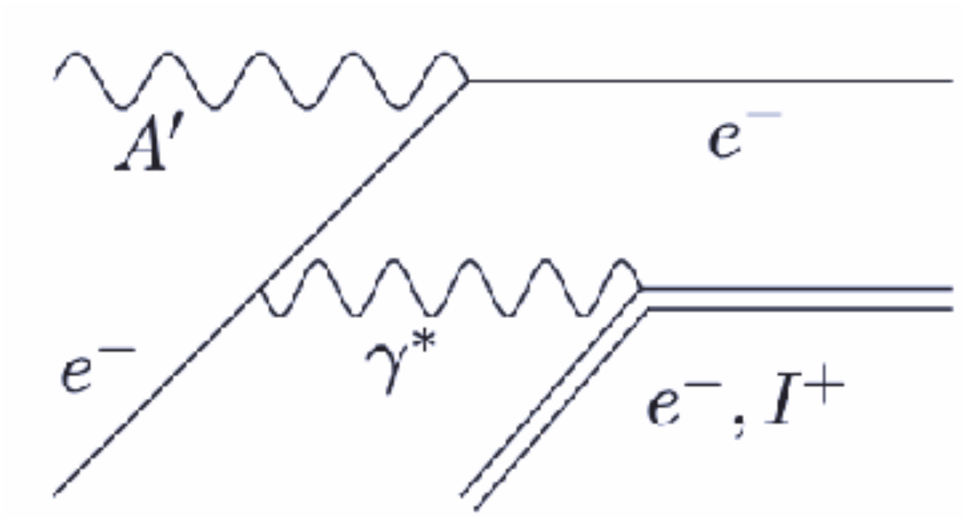


Light dark photons may even be **all of dark matter** itself: additional and distinct cosmological signatures.

Resonant Conversion into Photons

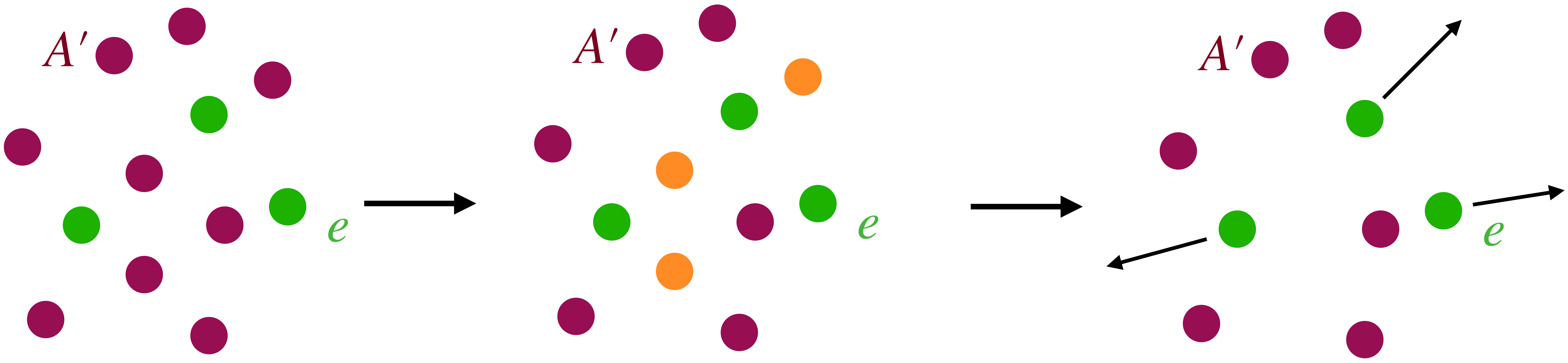


Oscillations convert A' dark matter
to **low frequency photons** which are **rapidly absorbed**.



$$\nu = 2.5\,\mathrm{Hz}\left(\frac{m_{A'}}{10^{-14}\,\mathrm{eV}}\right) \qquad \lambda_{\mathrm{mfp}} = \frac{140\,\mathrm{pc}}{(1+z)^6}\Delta_b^{-2}\left(\frac{T}{10^4\,\mathrm{K}}\right)^{3/2}\left(\frac{m_{A'}}{10^{-14}\,\mathrm{eV}}\right)^2$$

Free-Free Absorption



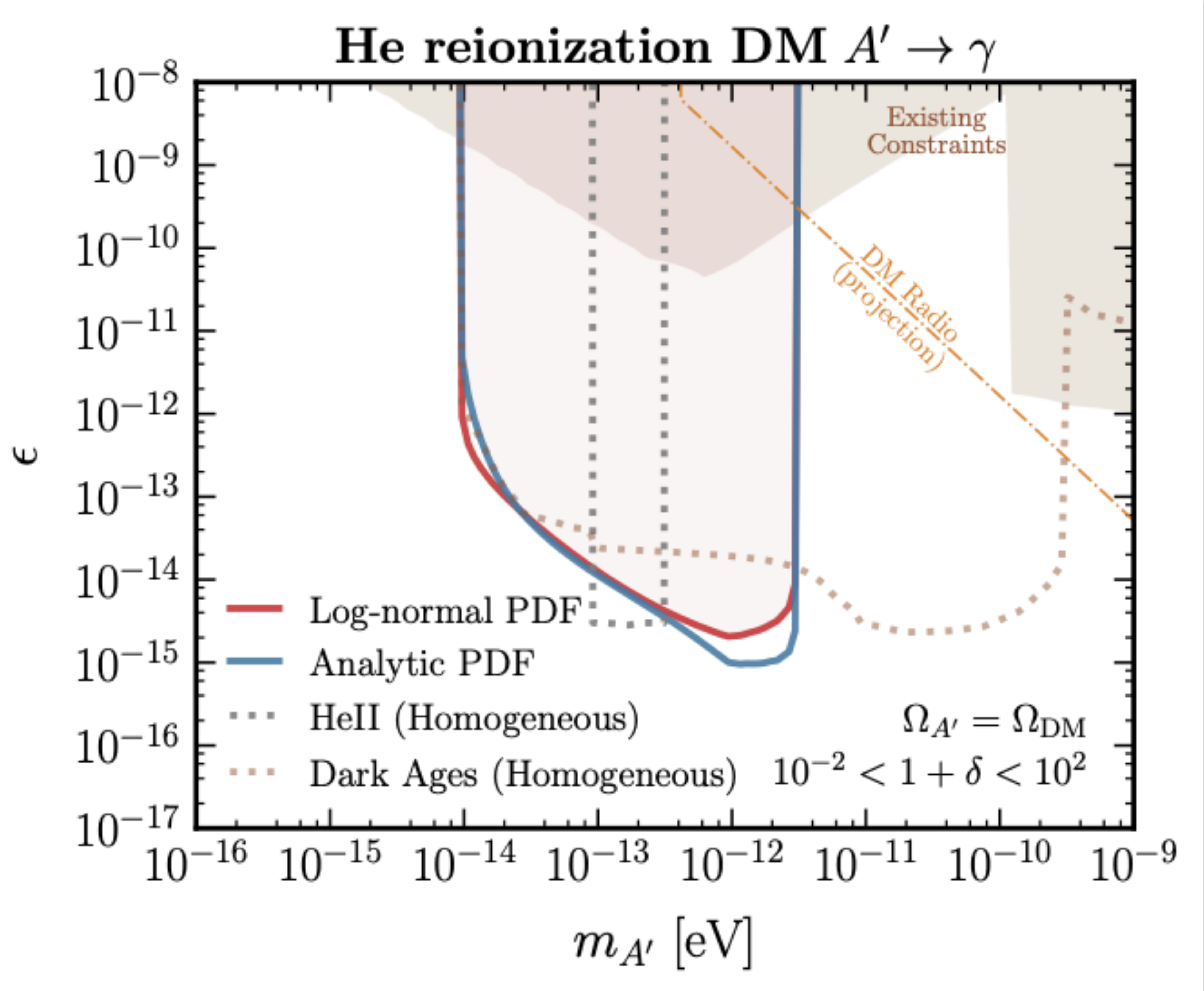
Before Resonant Conversion

Resonant Conversion

Free-Free Absorption (Inverse Bremsstrahlung)

Low-frequency photons **rapidly absorbed**, leading to strong **heating** of the gas. Can we detect this effect?

Intergalactic Medium Heating

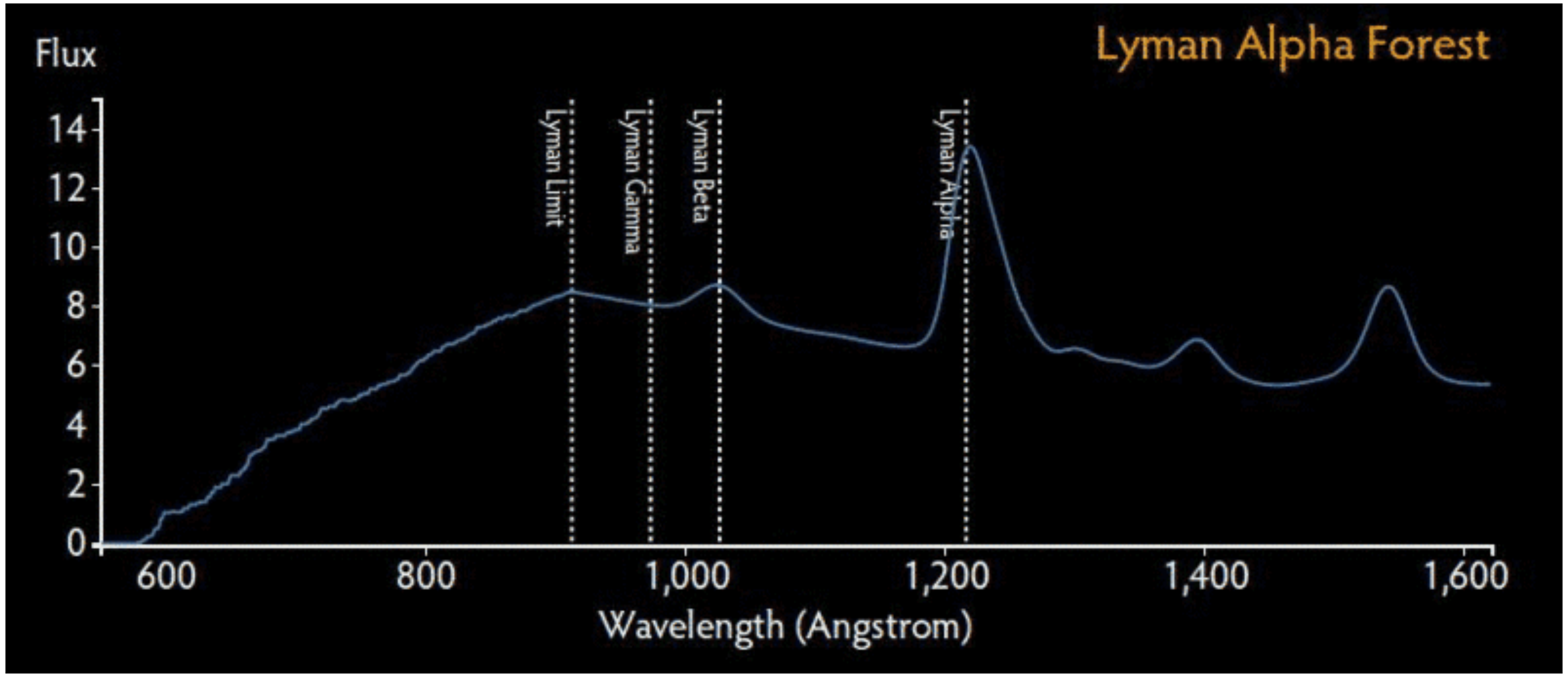


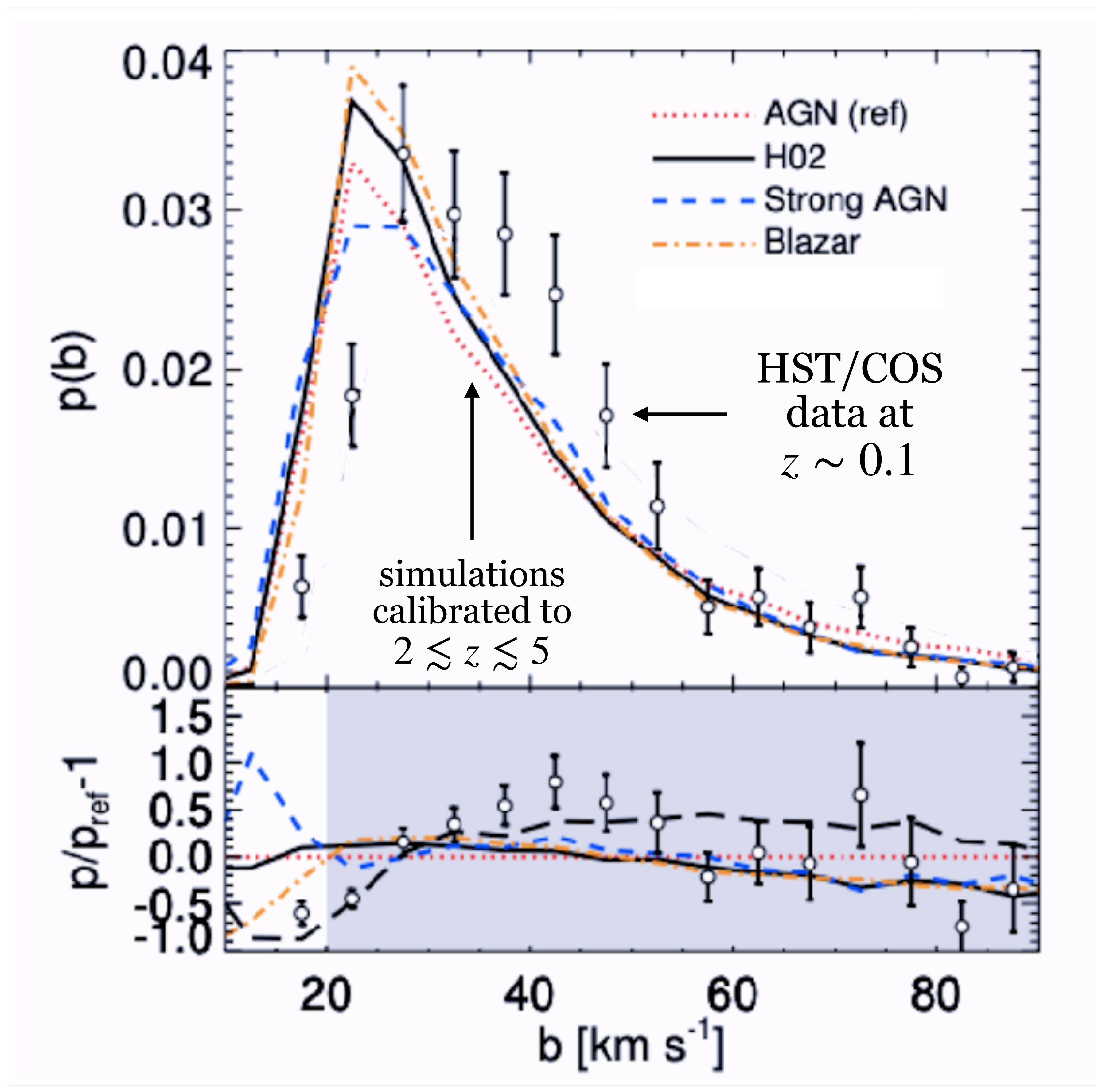
Dark matter $A' \to \gamma$ resonant conversions produce low-energy photons that heat the IGM.

Must include **inhomogeneities**.

Constraints can be roughly set by requiring $T_{\rm IGM} \lesssim 10^4$ K for consistency with $2 \lesssim z \lesssim 5$ Lyα forest.

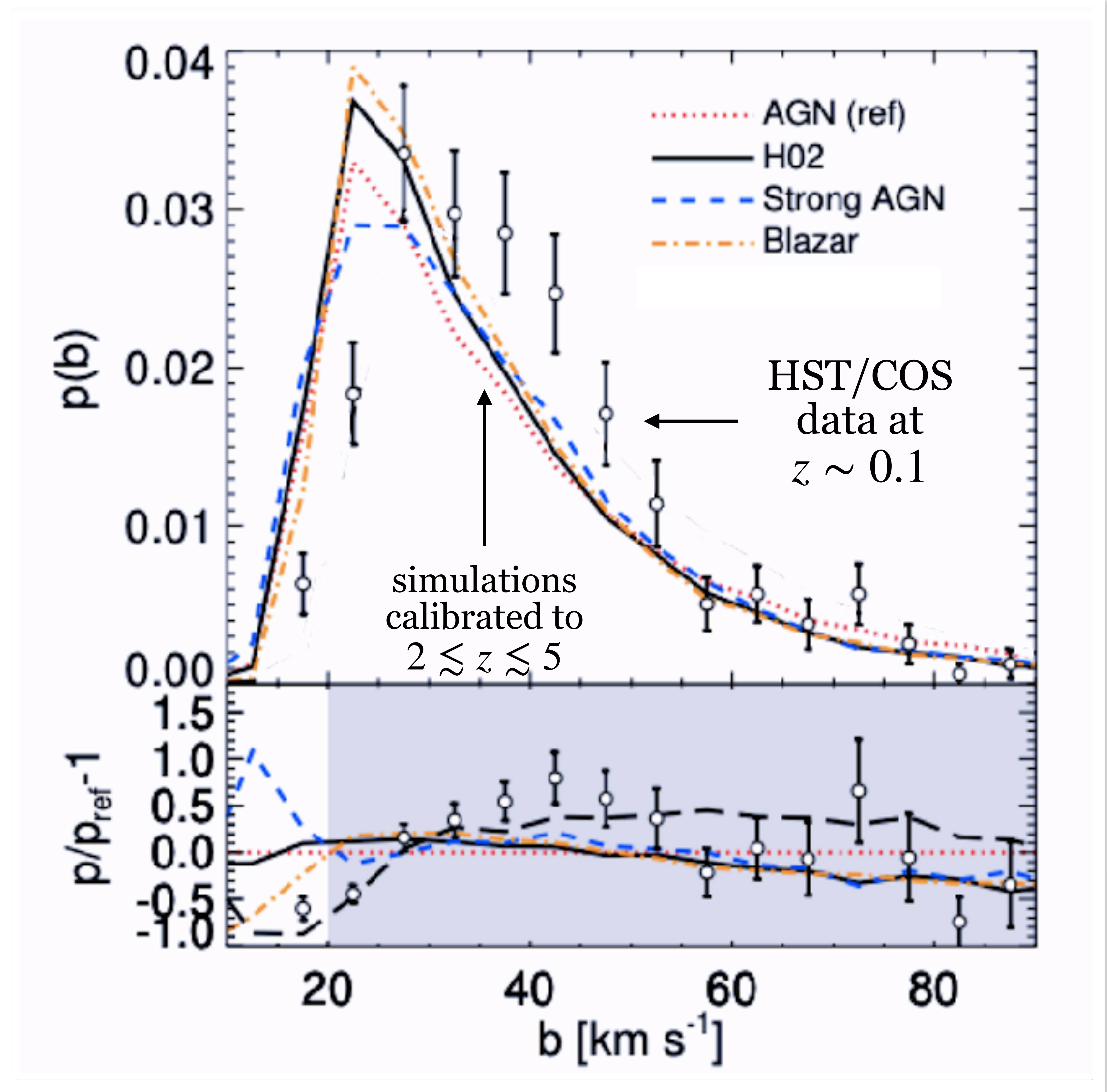
Low-Redshift Lyα Discrepancy

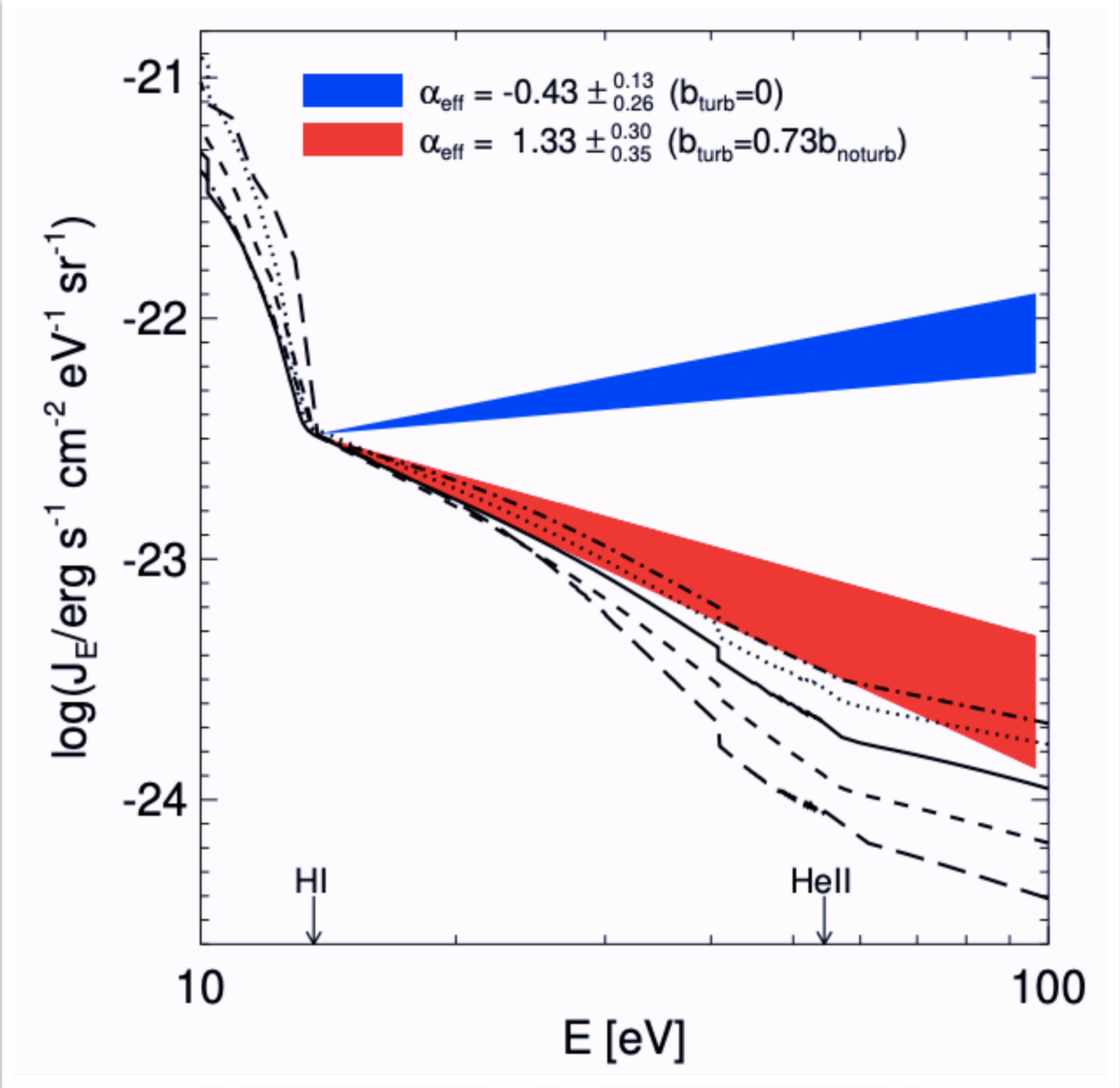




IGM simulations find Lyα Doppler widths that are **too narrow** at low redshifts compared to observations.

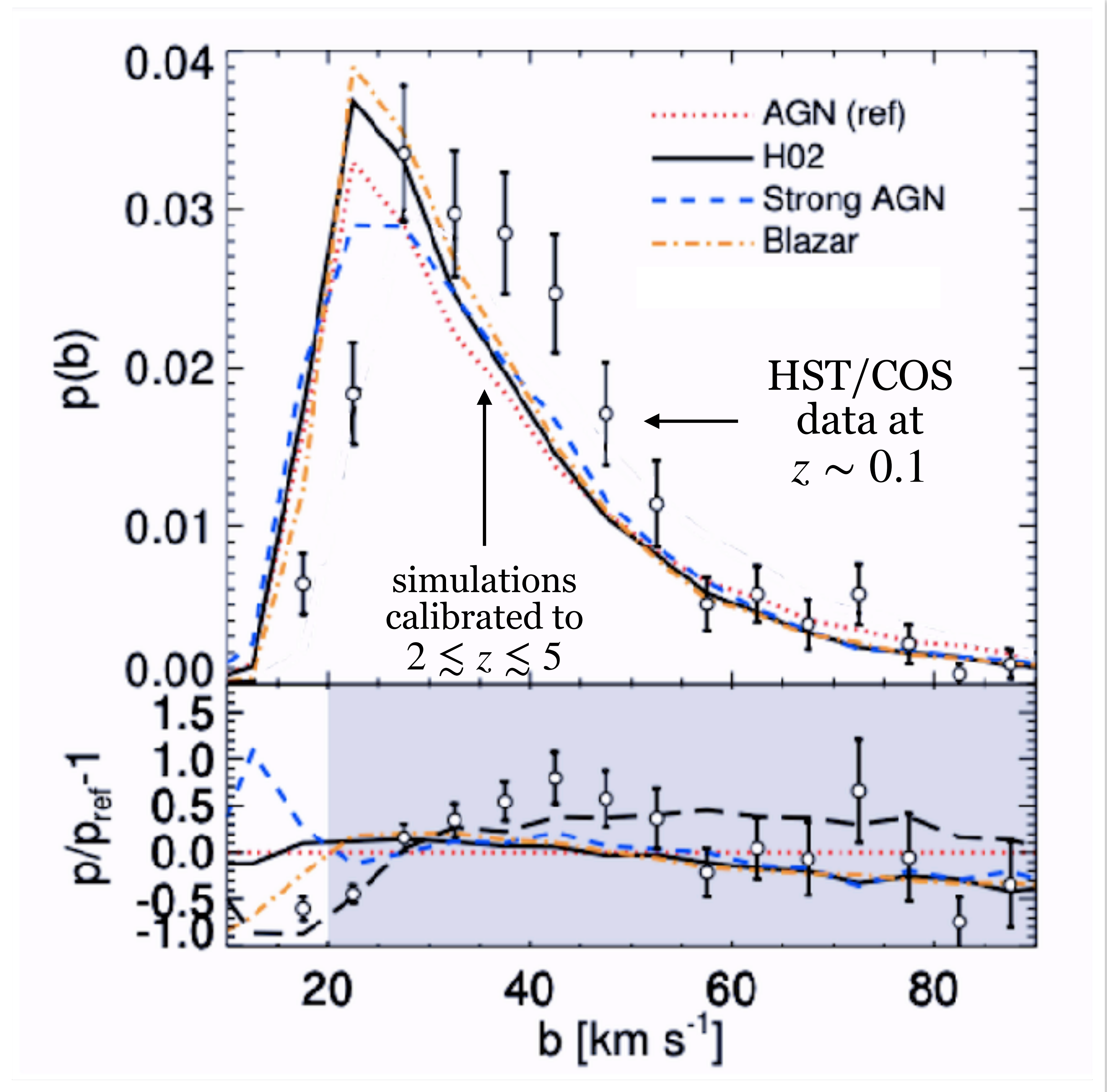
Low-Redshift Lyα Discrepancy

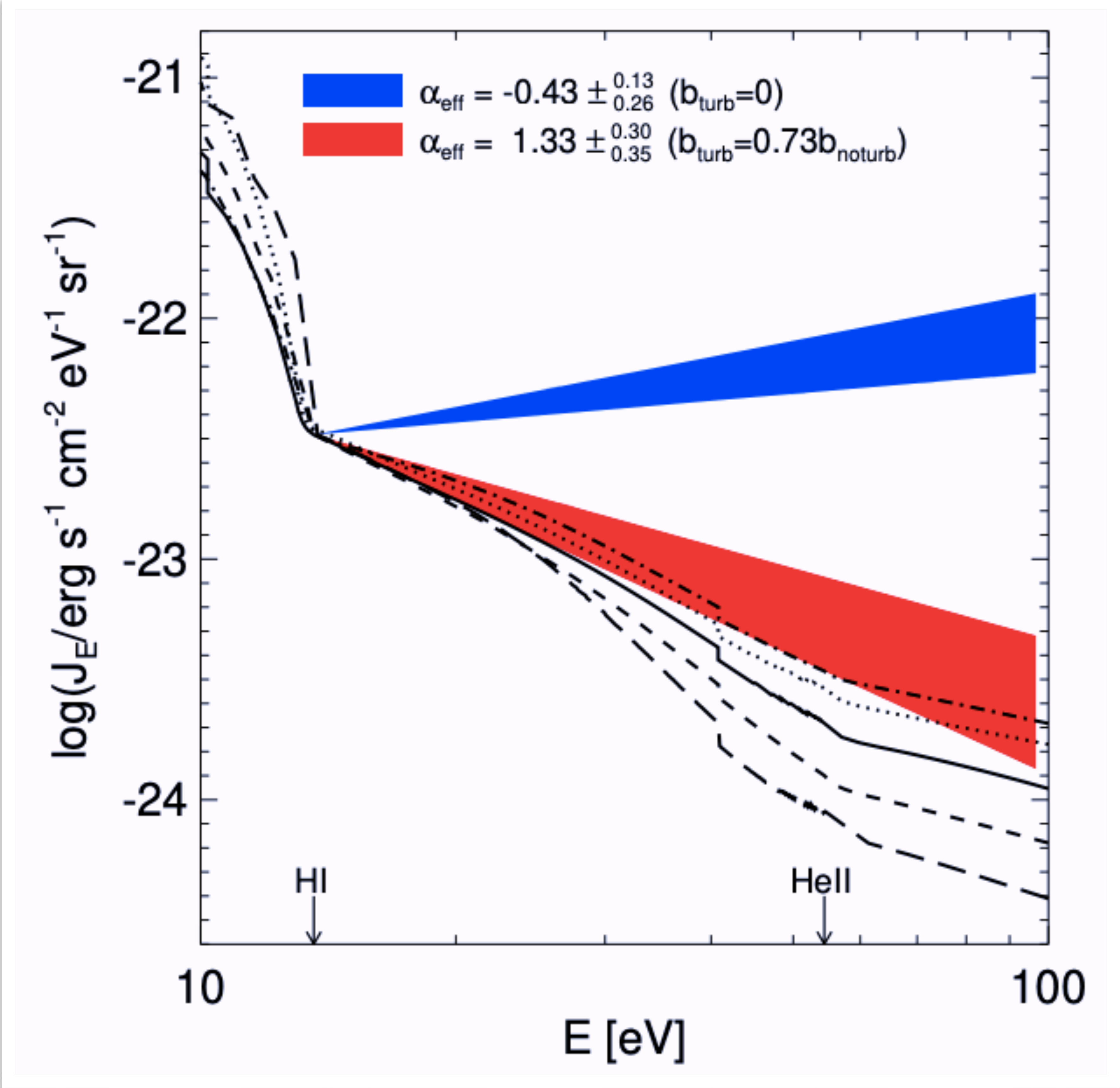




Cannot be explained by increased feedback, or steeper ionizing radiation spectrum.

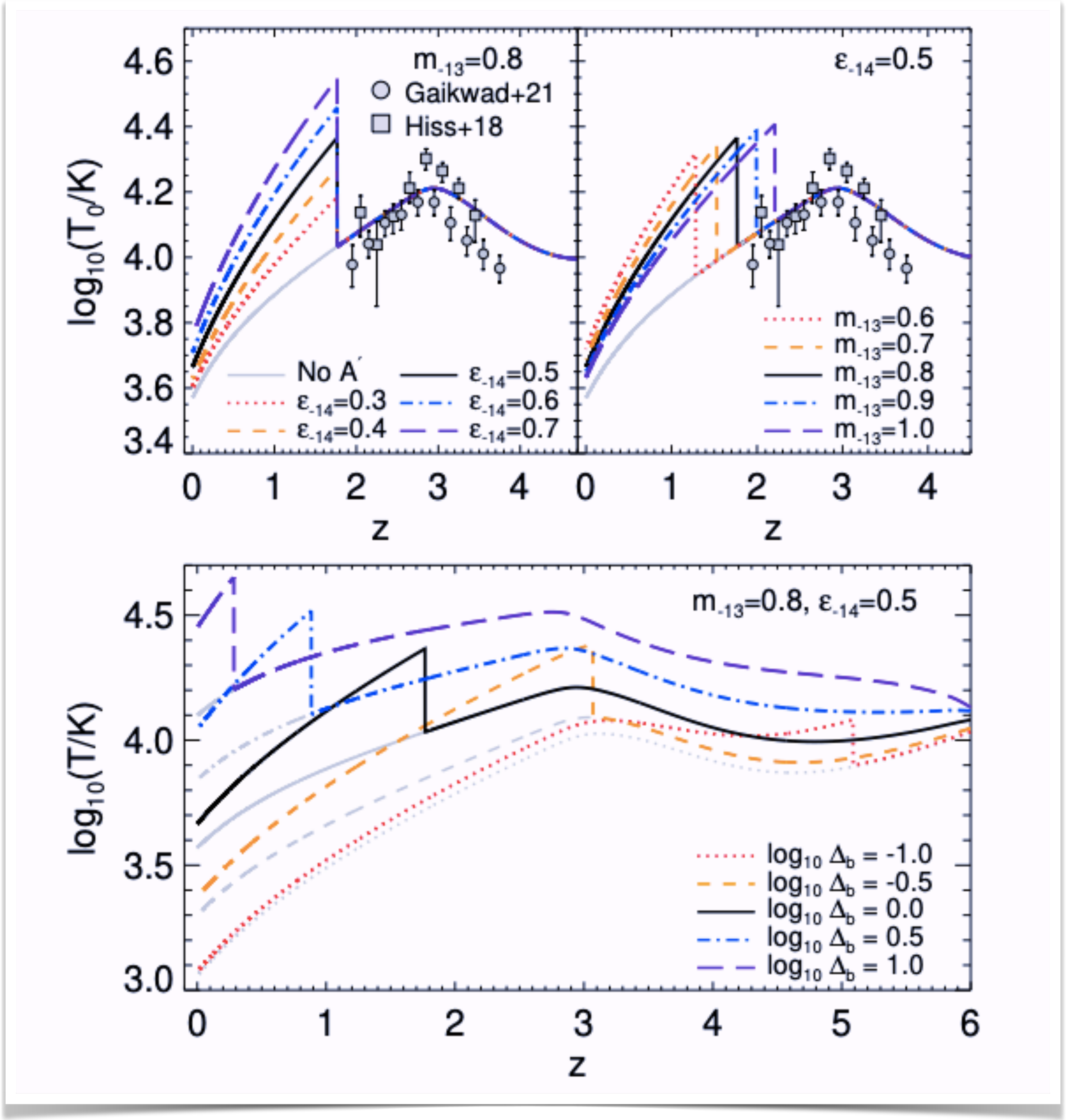
Low-Redshift Lyα Discrepancy





Requires $u = 6.9$ eV per baryon on average for $z \lesssim 2$, with density dependence $u \propto \Delta^{0.6}$. Possibly: turbulence, dust.

Dark Photon Dark Matter Heating



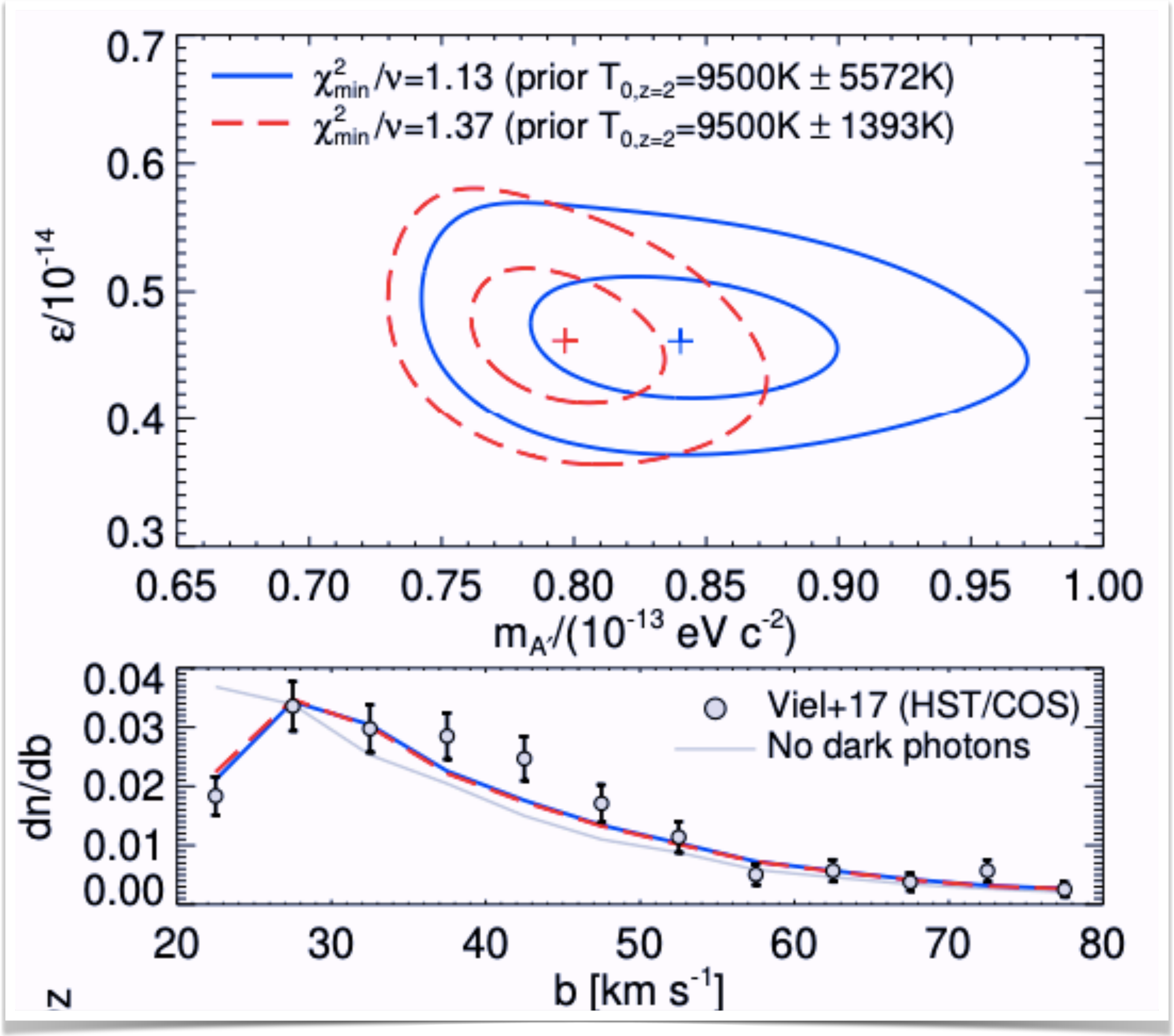
$$P_{A' \to \gamma} = \pi \epsilon^2 m_{A'} \left| \frac{d \ln m_\gamma^2}{dt} \right|^{-1}_{m_{A'} = m_\gamma}$$

Dark matter $A' \to \gamma$ conversions can give anomalous heating.

$m_{A'} \lesssim 8 \times 10^{-14}\,\mathrm{eV}$ to be consistent with Lyα forest at $2 \lesssim z \lesssim 5$.

$u \propto \Delta^{1/2}$ due to photon plasma mass evolution.

Dark Photon Dark Matter Heating



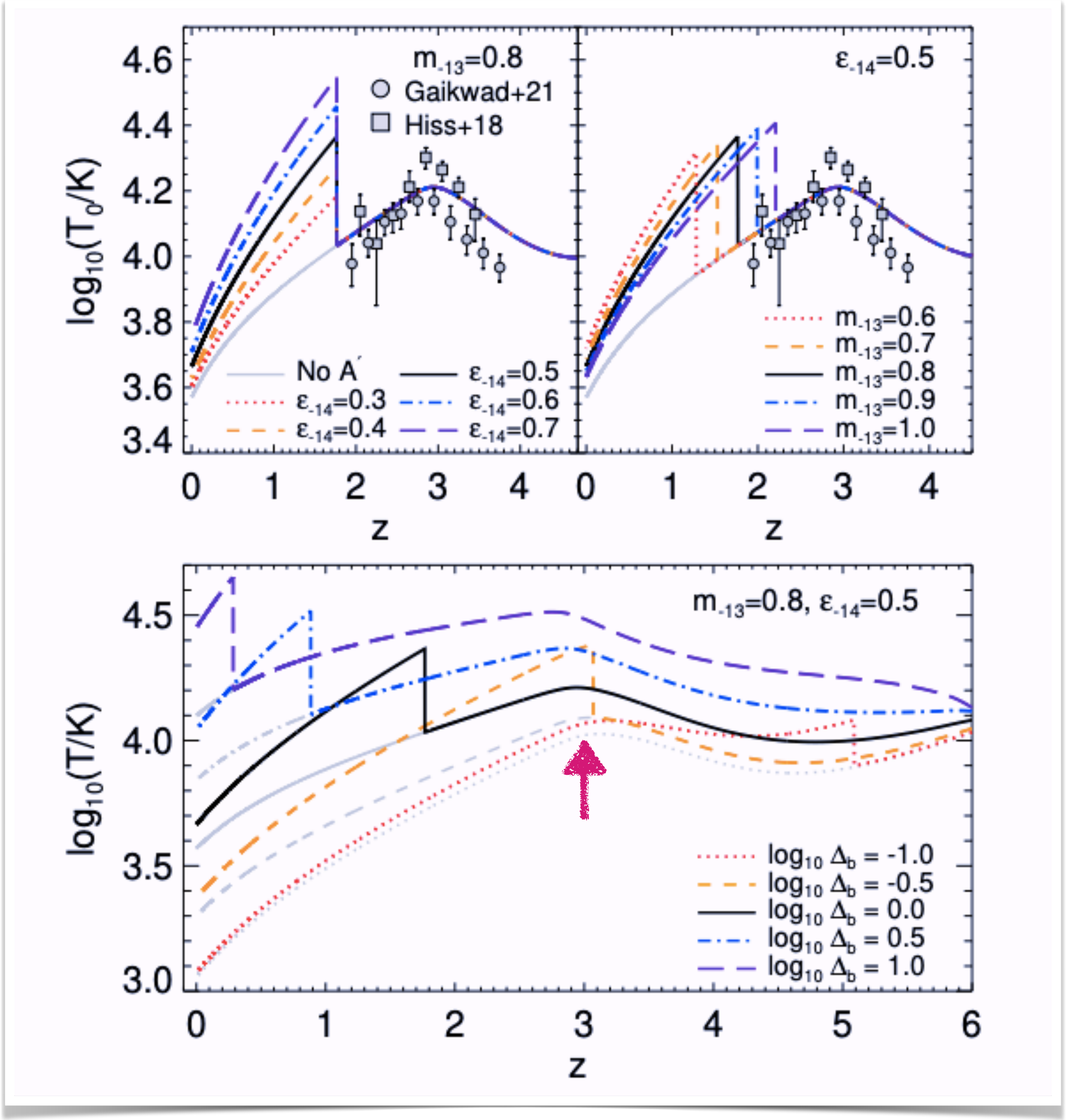
Significantly better agreement with HST/COS Doppler widths.

Future Work

Predicts **inverted temperature-density relation** at $z \sim 3$, for which we have mild evidence for (Rorai+).

Use these simulations to set **robust limits on A' DM**, improving on current estimates.

Stay tuned!



$\gamma \to A'$: **CMB is an excellent probe.**

A' **DM** $\to \gamma$: **Heating effect potentially detected in Ly-α forest.**